MiniBooNE's First Neutrino Oscillation Result

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Particle Physics and Particle Astrophysics Seminar
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University of Sheffield

Outline

1. Motivation and Introduction
2. Description of the Experiment
3. Analysis Overview
4. Two Independent Oscillation Searches
5. First Results
6. Updates Since First Result

Motivation

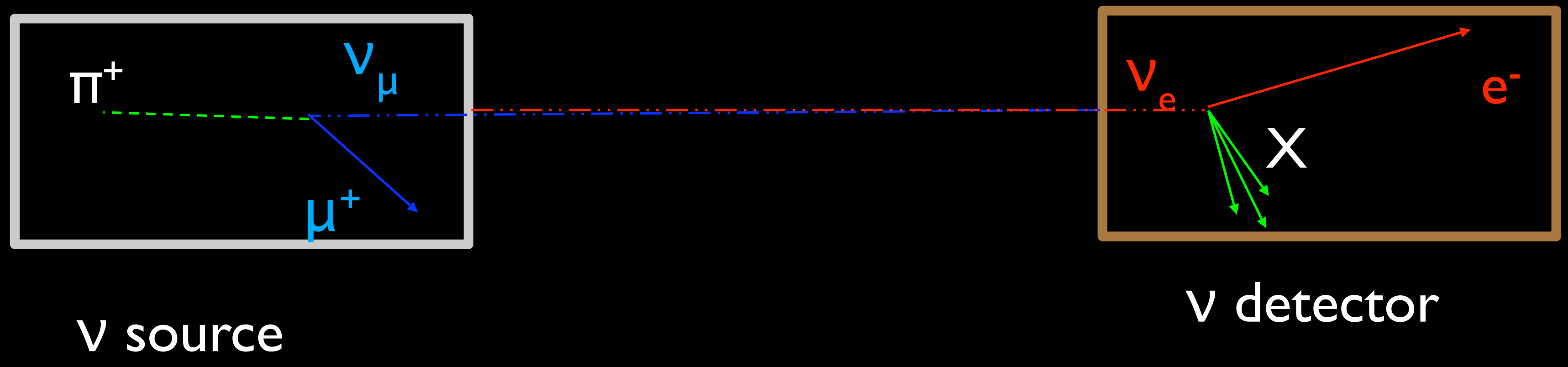
if neutrinos have mass...

a neutrino that is produced as a ν_μ

- (e.g. $\pi^+ \to \mu^+ \nu_\mu$)

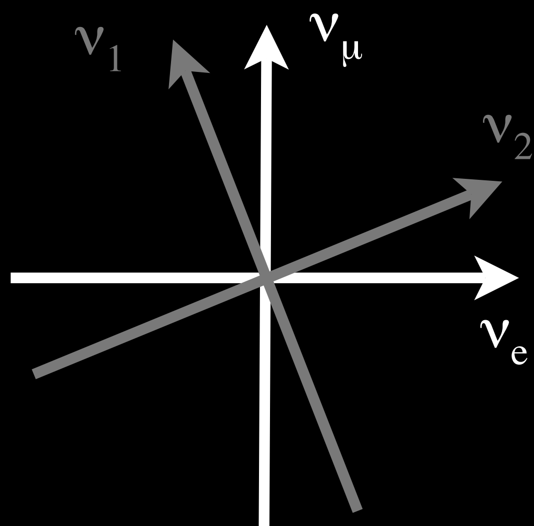
might some time later be observed as a ν_e

- (e.g. $\nu_e\, n \to e^- p$)



Neutrino Oscillation

$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



- Consider only two types of neutrinos
- If weak states differ from mass states
  - i.e. $(\nu_\mu\ \nu_e) \neq (\nu_1\ \nu_2)$
- Then weak states are mixtures of mass states

$$|\nu_\mu(t)> = -\sin\theta|\nu_1> e^{-iE_1 t} + \cos\theta|\nu_2> e^{-iE_2 t}$$

- Probability to find ν_e when you started with ν_μ

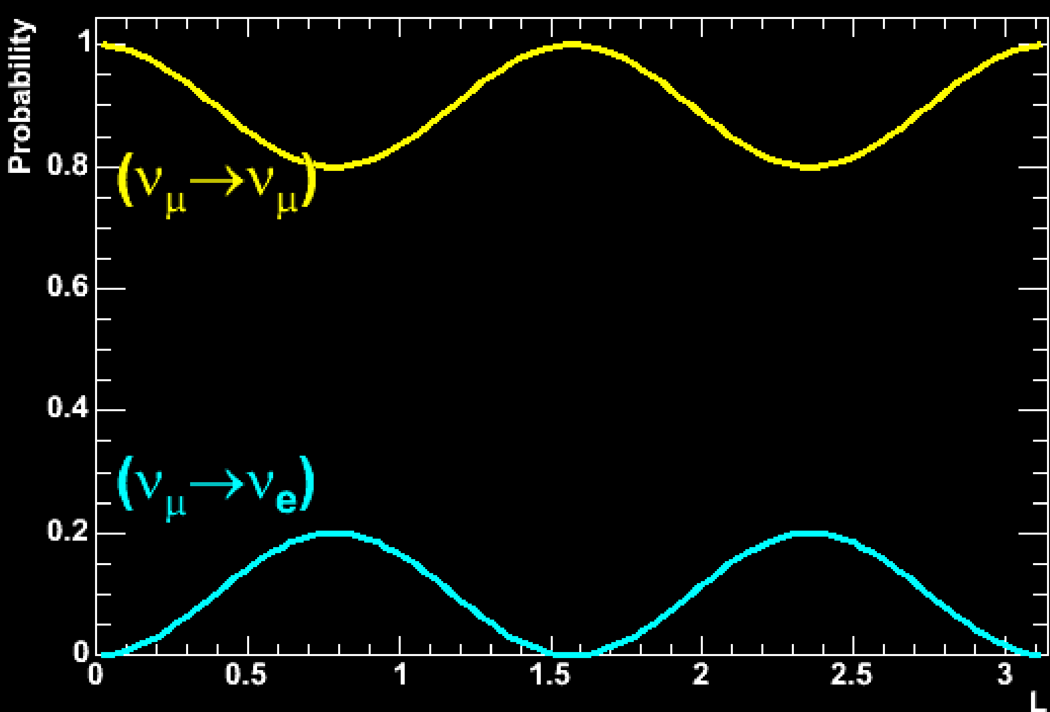
$$P_{osc}(\nu_\mu \to \nu_e) = |<\nu_e|\nu_\mu(t)>|^2$$

Neutrino Oscillation

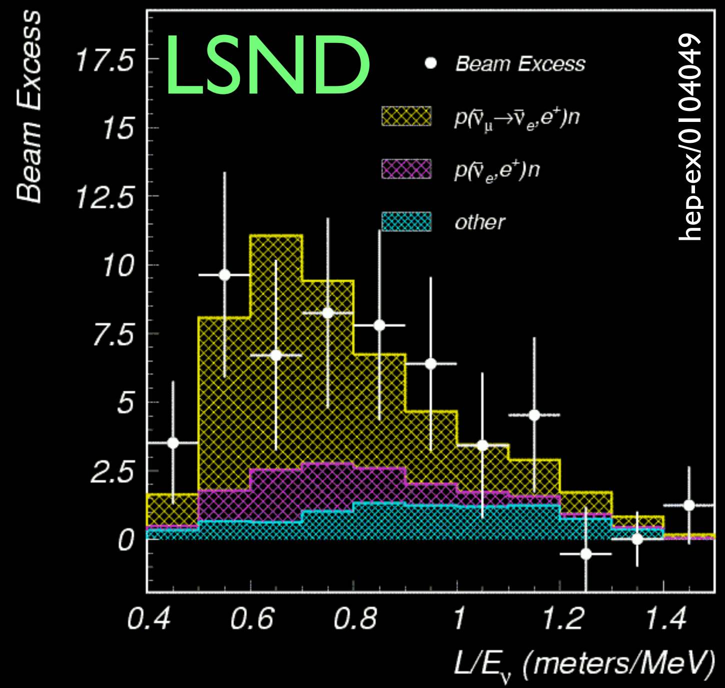
- In units that experimentalists like:

$$P_{osc}(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$

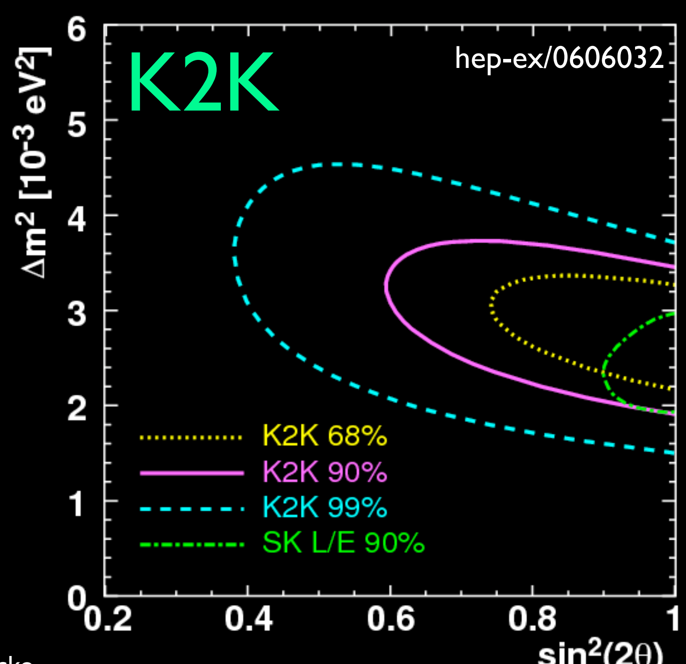
- Fundamental Parameters
  - mass squared differences
  - mixing angle
- Experimental Parameters
  - L = distance from source to detector
  - E = neutrino energy

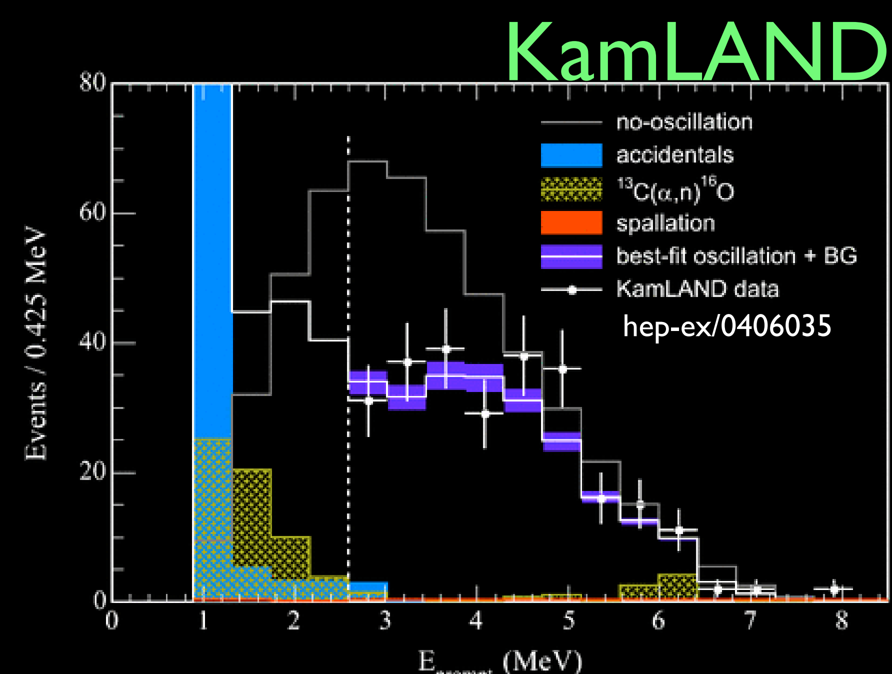


Oscillation Signals



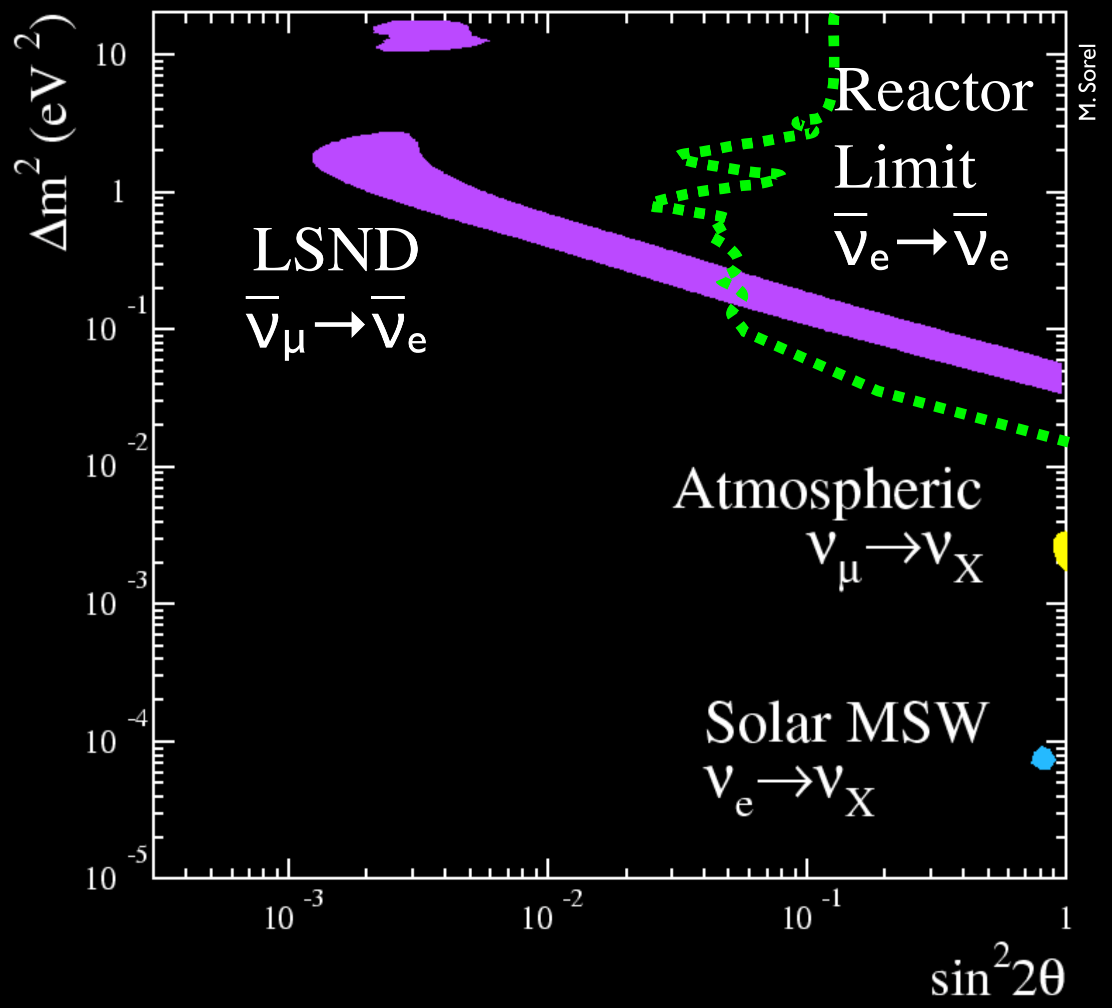
- Solar - Homestake, ... SNO
  - confirmed by reactors
- Atmospheric - Super-K, ...
  - confirmed by accelerators
- Accelerator - measured by LSND
  - unconfirmed!





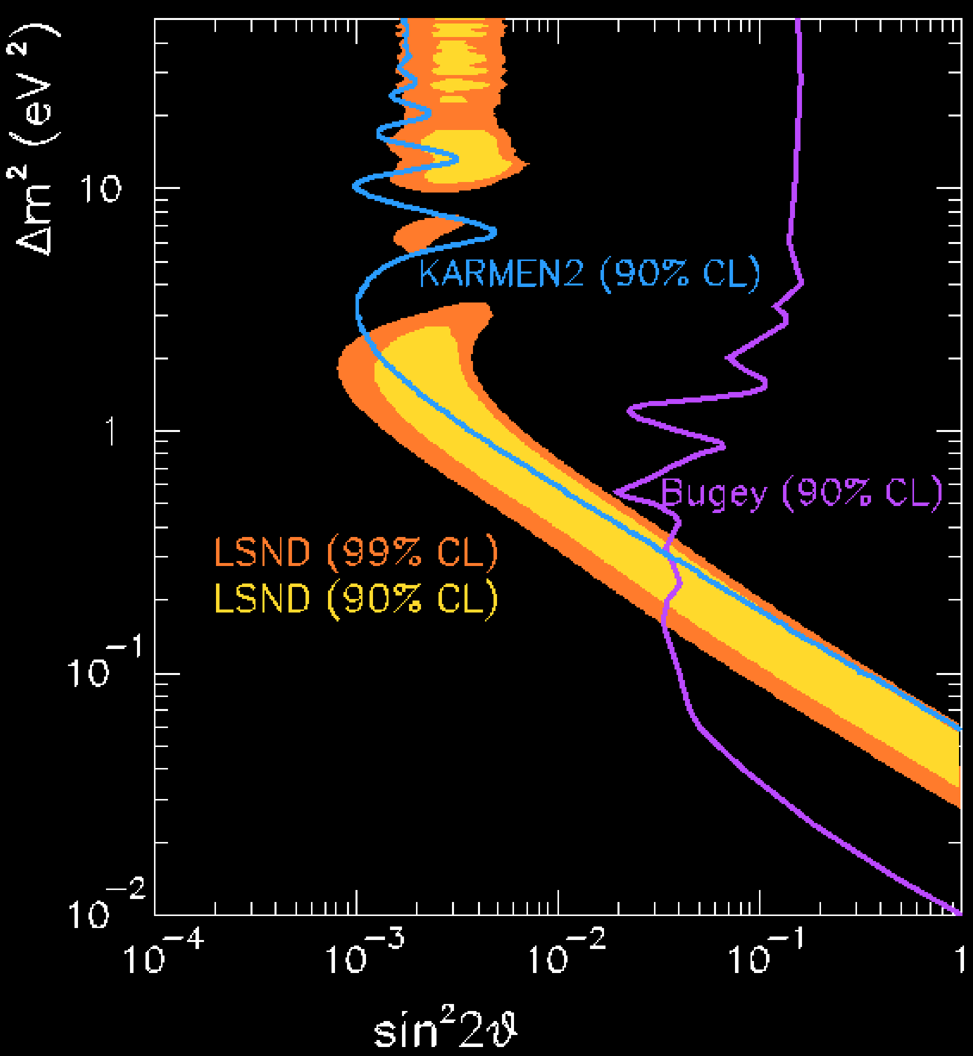
The Problem

- Three different neutrino oscillation signals
- Three independent Δm^2
- Problem:
  We only need two!
- Explanation requires physics well beyond the standard model
- Is it true?



Verifying LSND

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$



- LSND interpreted as 2 ν oscillation
- Verification requires same (L/E) and high statistics
    - Different systematics
- MiniBooNE chose higher L and E
- Strategy: search for ν_e excess in ν_μ beam

MiniBooNE Collaboration

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Fermilab Visual Media Services

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TODAY: MiniBooNE's initial results on testing the LSND anomaly

1- Generic search for ν_e excess in ν_μ beam

2- Analysis of data within 2 ν appearance only context

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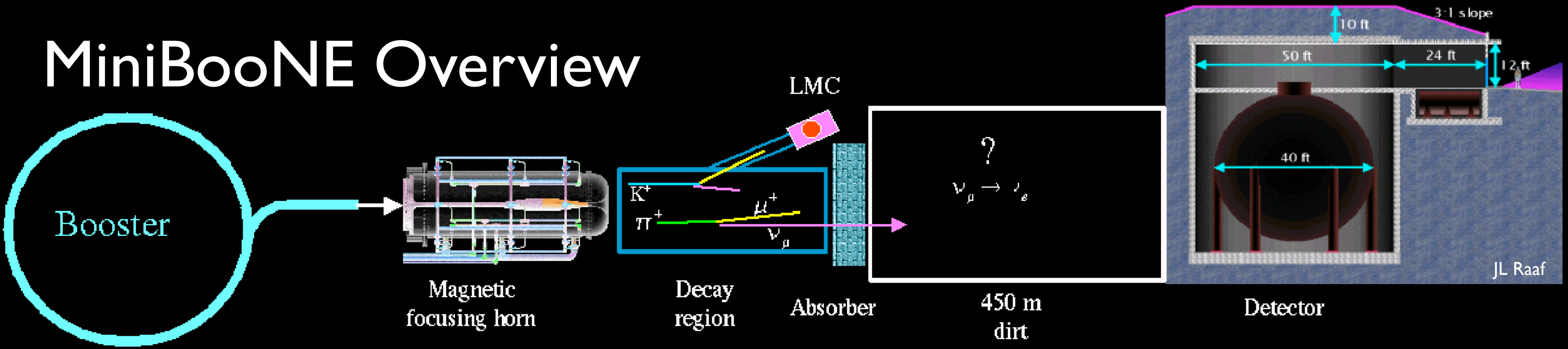
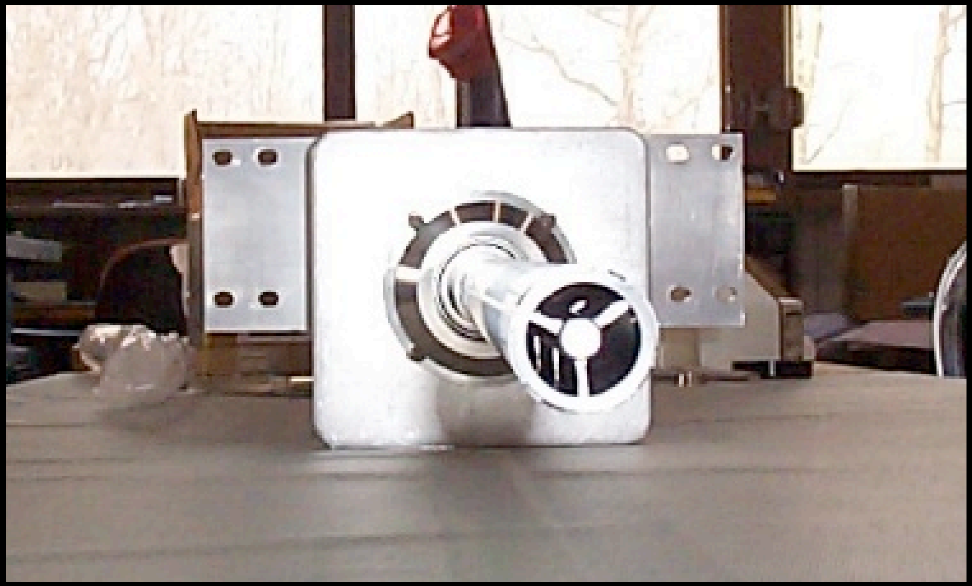
Overview

MiniBooNE Overview



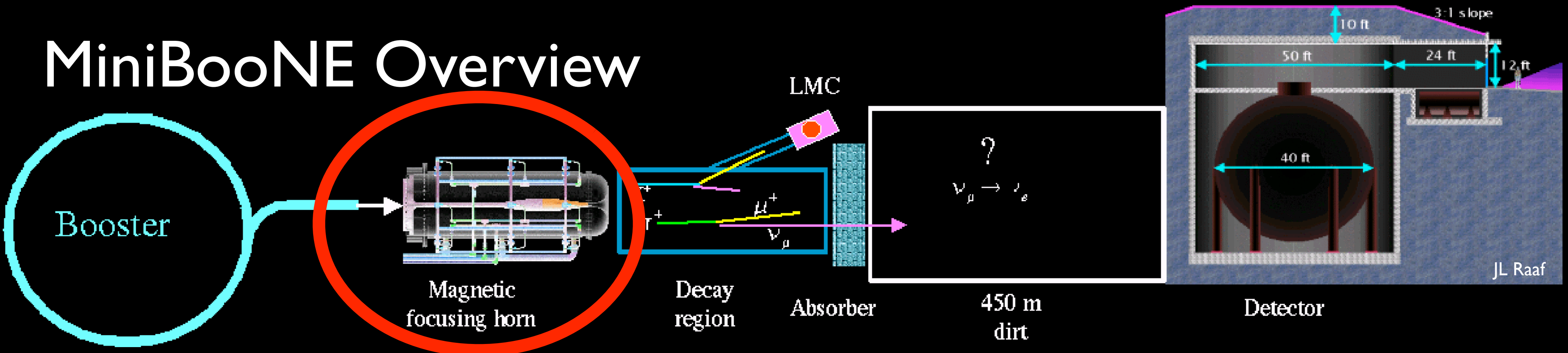
Target & Horn



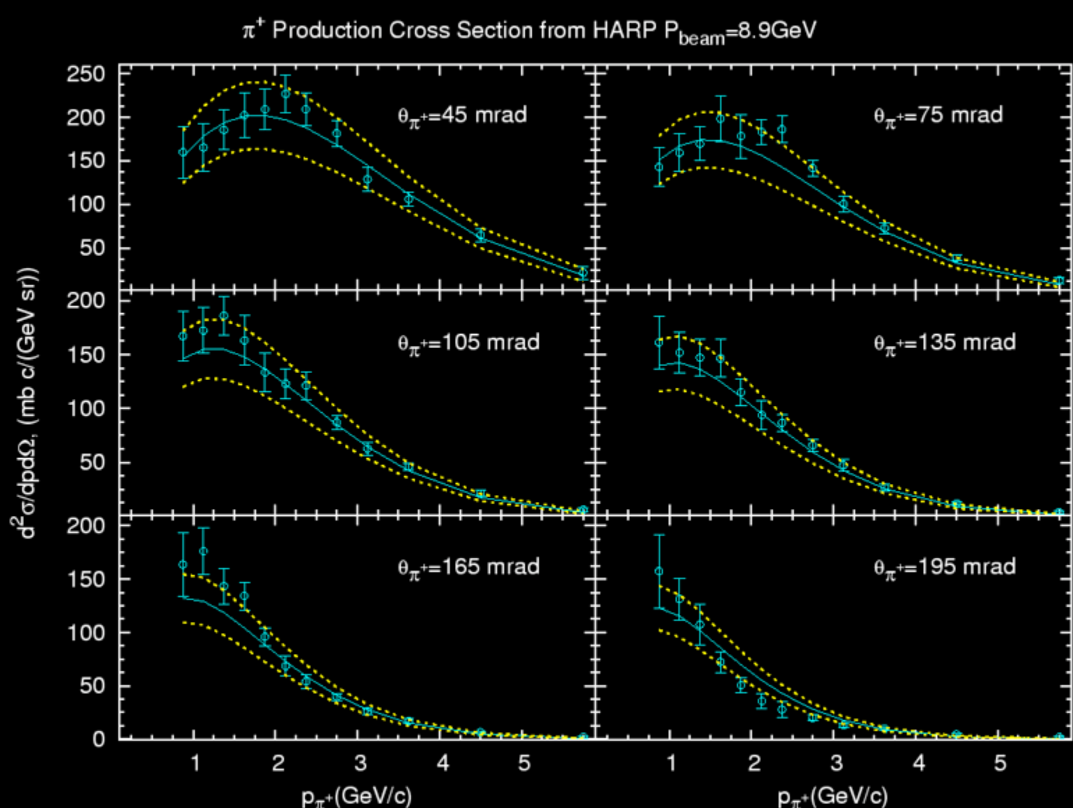
Main components of Booster Neutrino Beam (BNB)

(96M and 146M+ pulses)

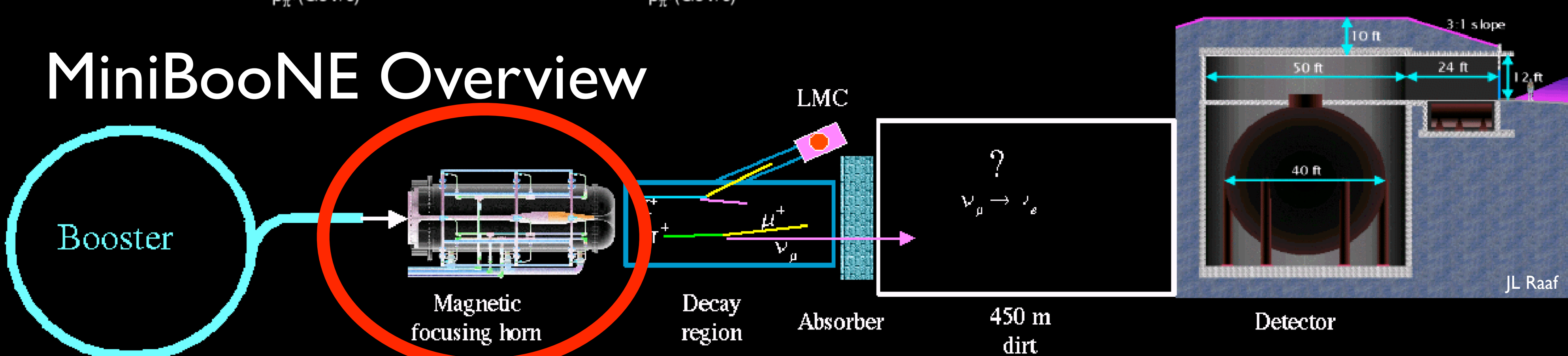
MiniBooNE Overview



Meson Production

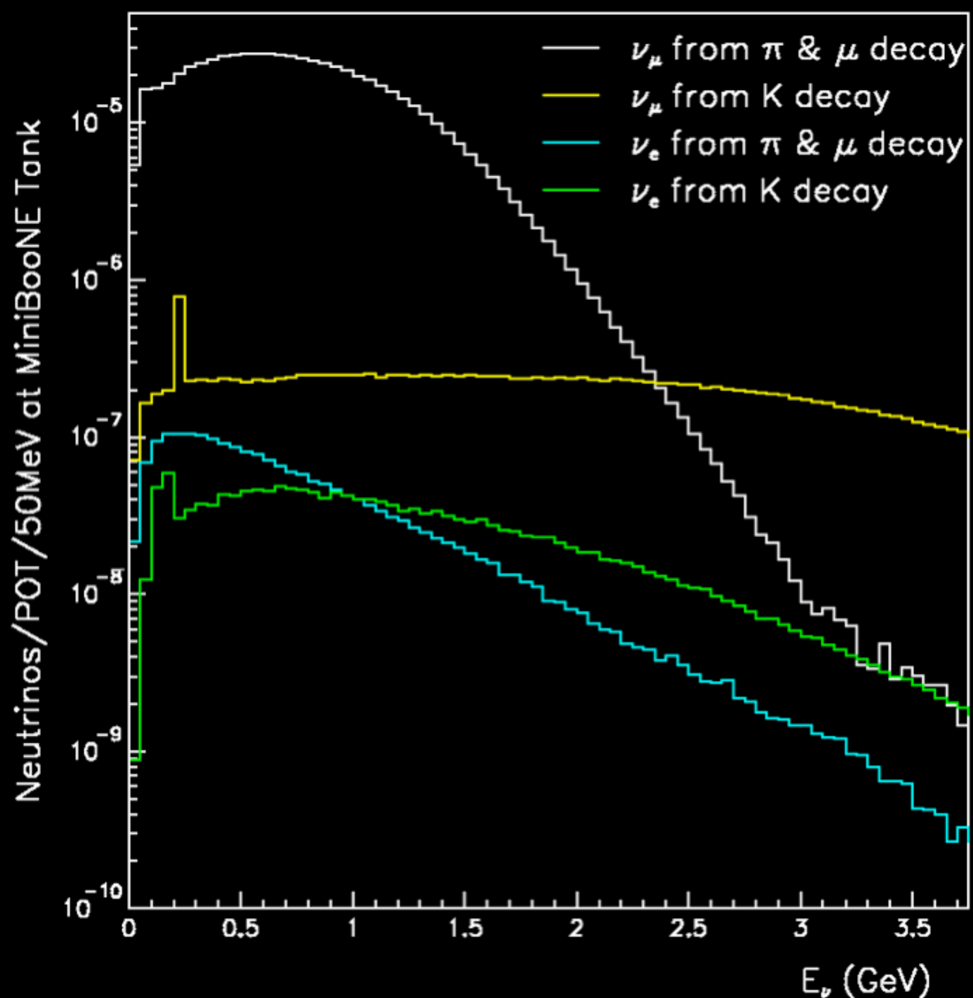


- External meson production data
    - HARP data (CERN)
- Parametrisation of cross-sections
    - Sanford-Wang for pions
    - Feynman scaling for kaons

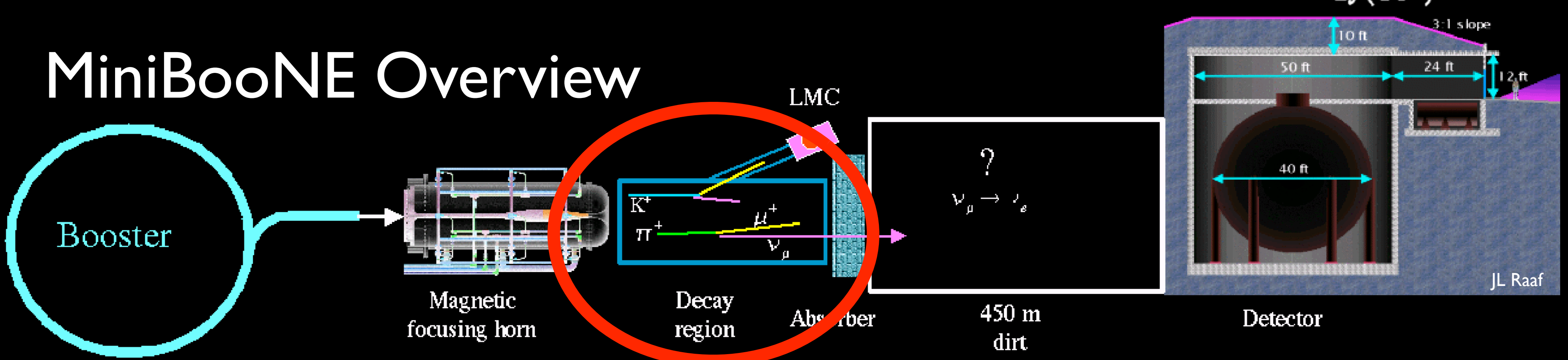


ν Flux

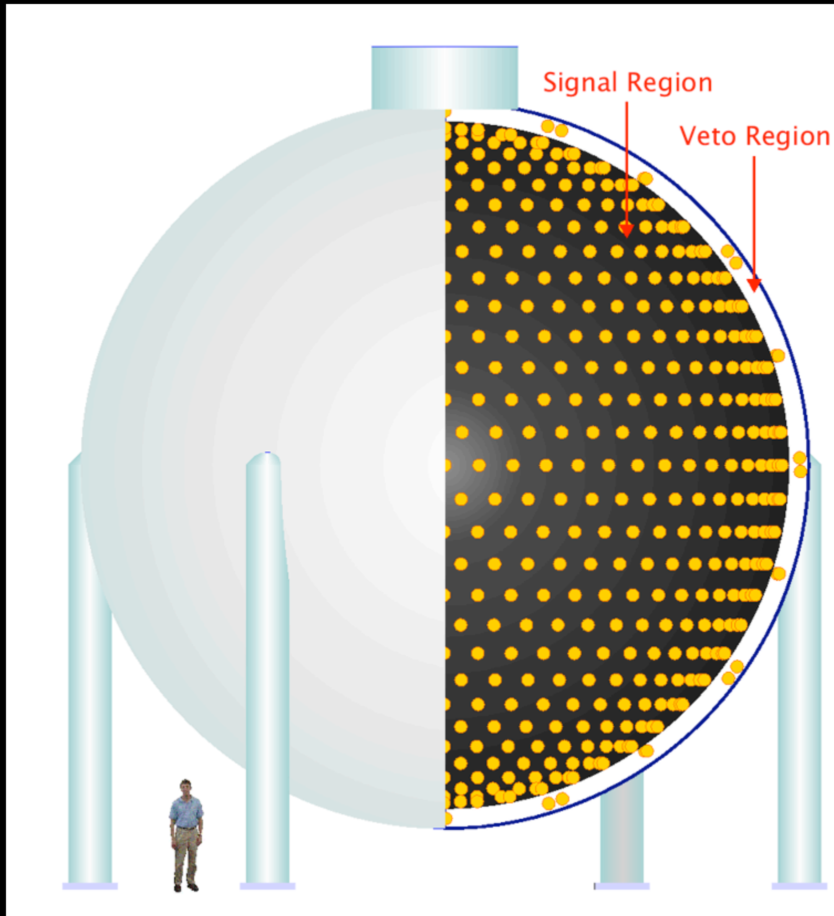
- 99.5% pure muon flavour
- 0.5% intrinsic ν_e
- Constrain ν_e content with ν_μ measurements

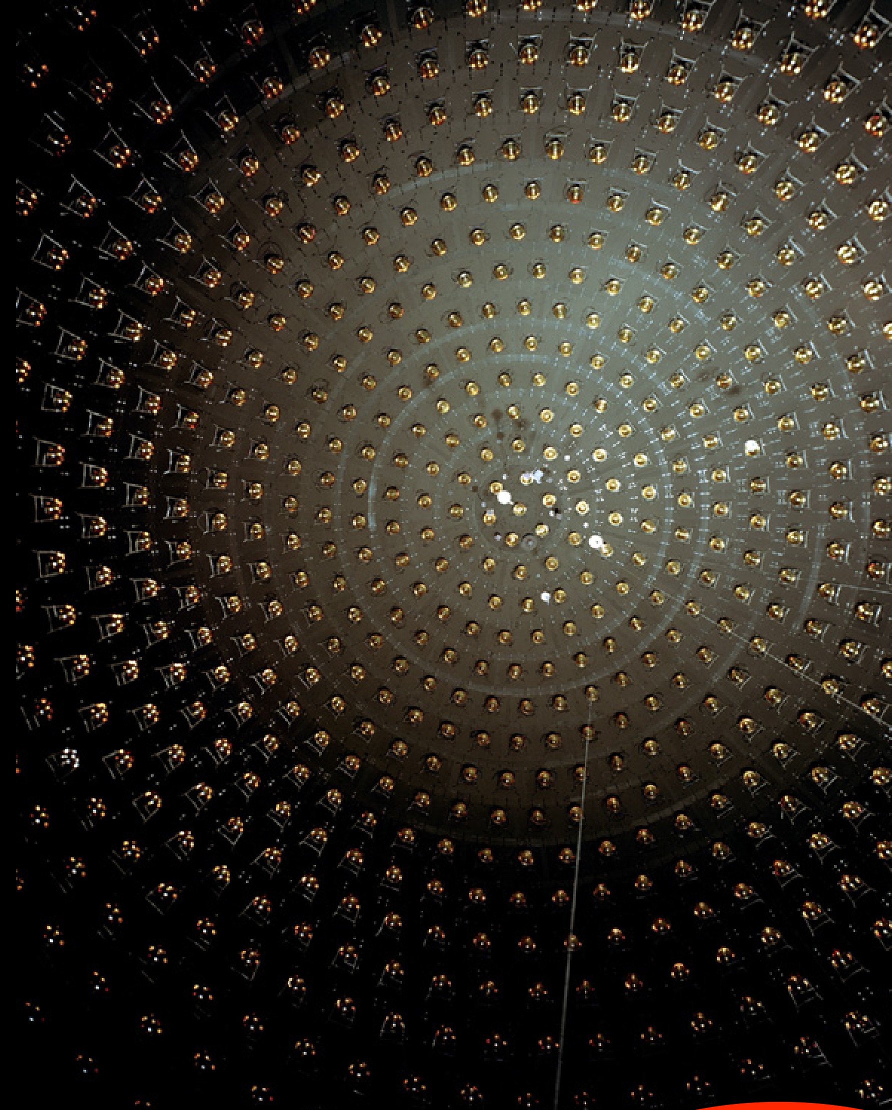


MiniBooNE Overview

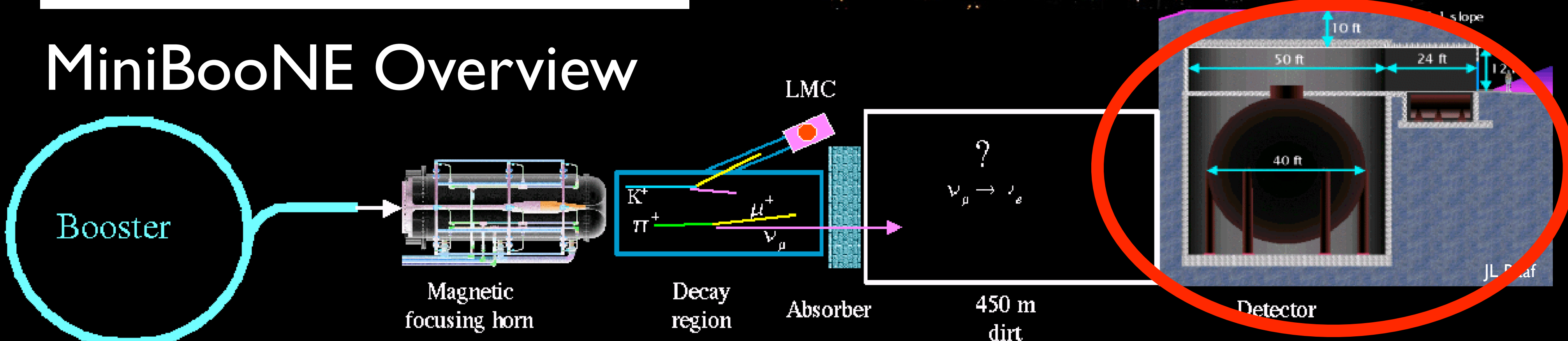


Detector

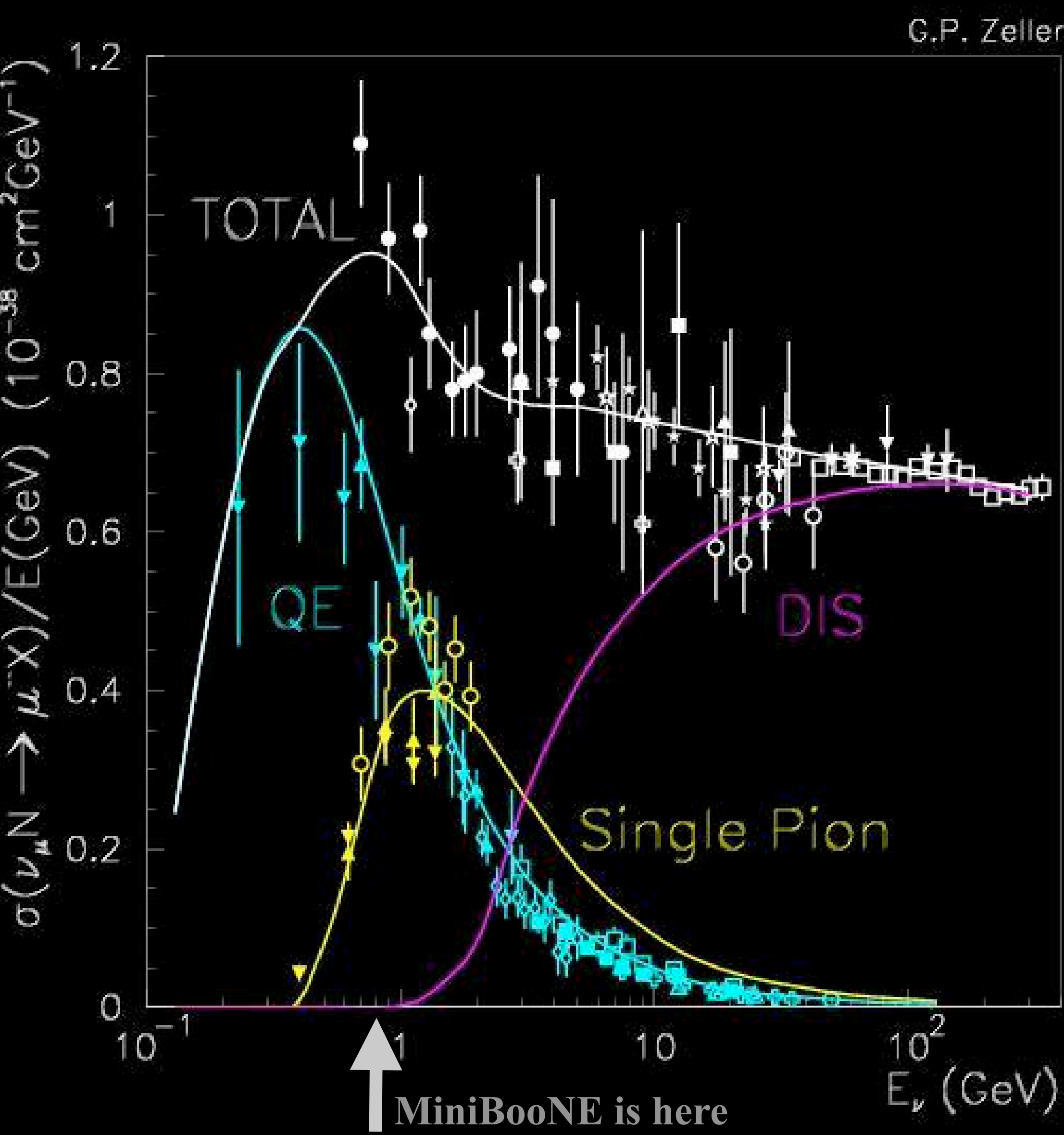


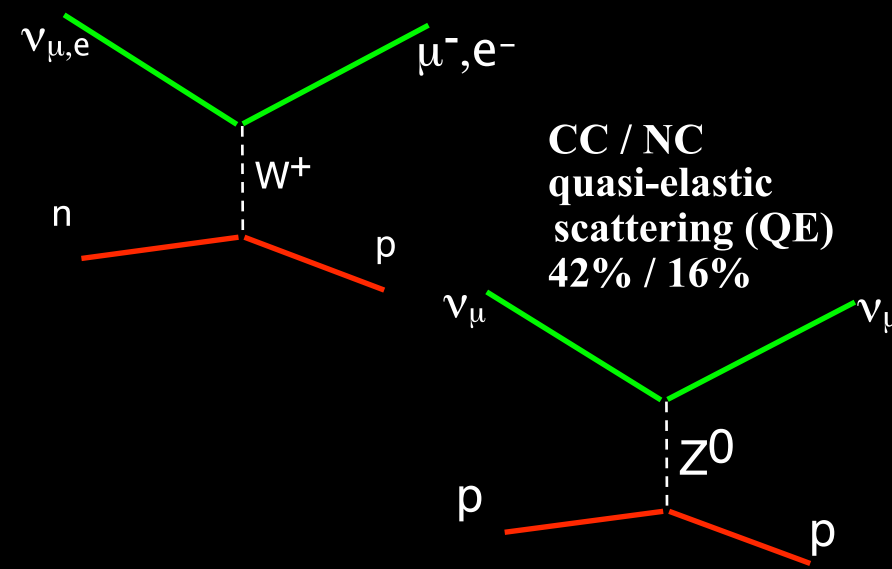


MiniBooNE Overview

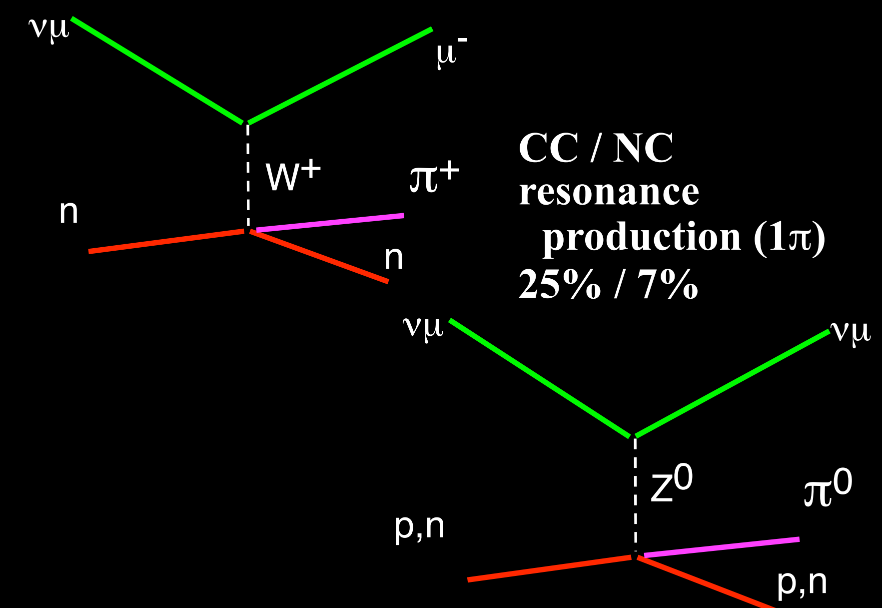


Neutrino Interactions





CC / NC quasi-elastic scattering (QE) 42% / 16%

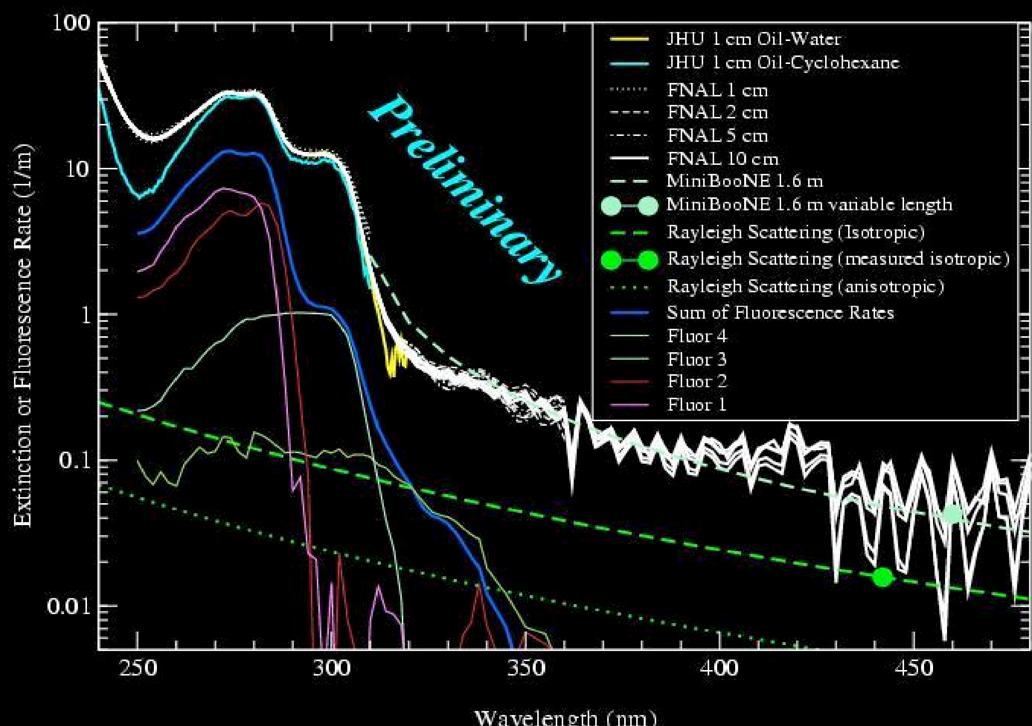


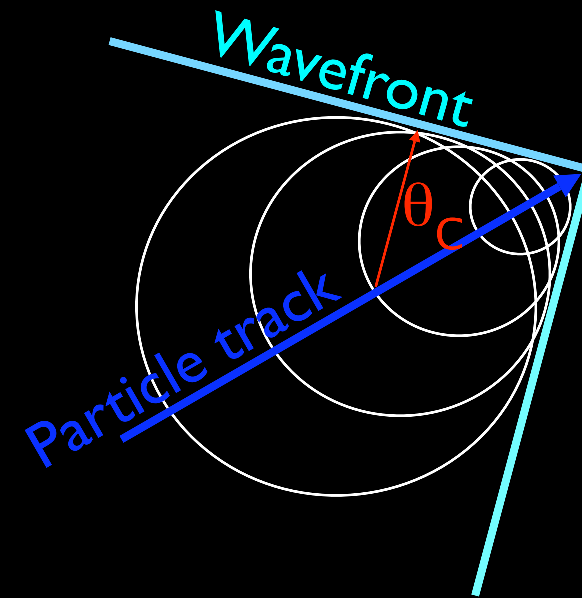
CC / NC resonance production (1π) 25% / 7%

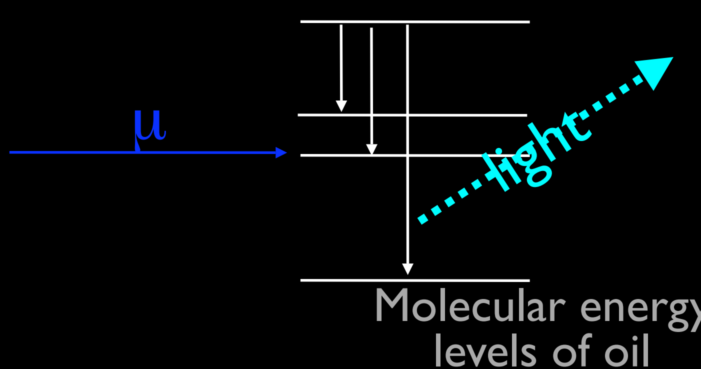
Mineral Oil Optics

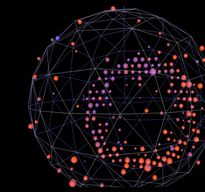
- Production:
    - Cherenkov and scintillation
- Secondary:
    - Fluorescence and scattering (Raman, Rayleigh)

Extinction Rate for MiniBooNE Marcol 7 Mineral Oil



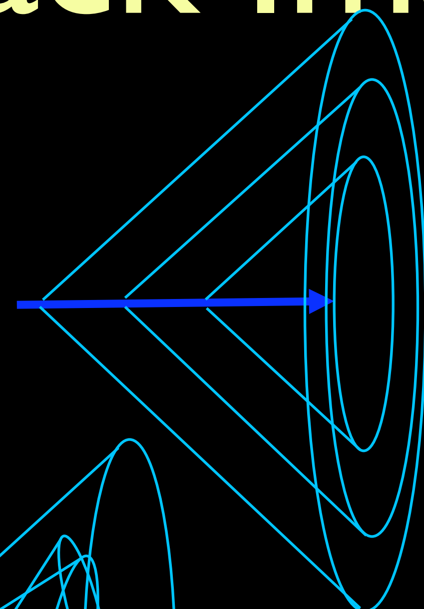


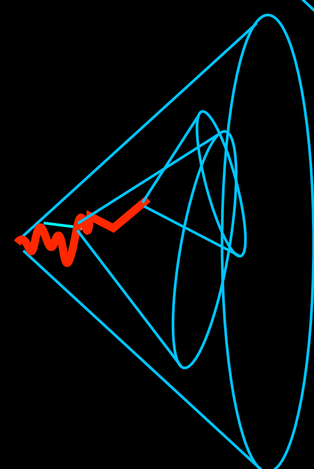


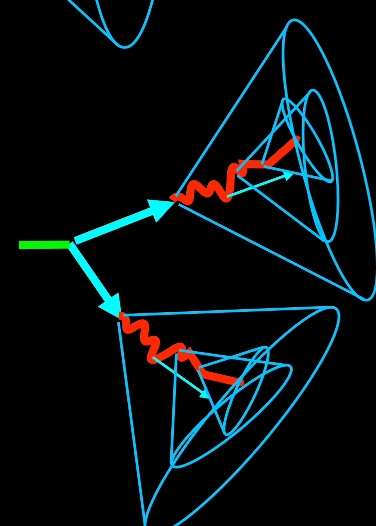


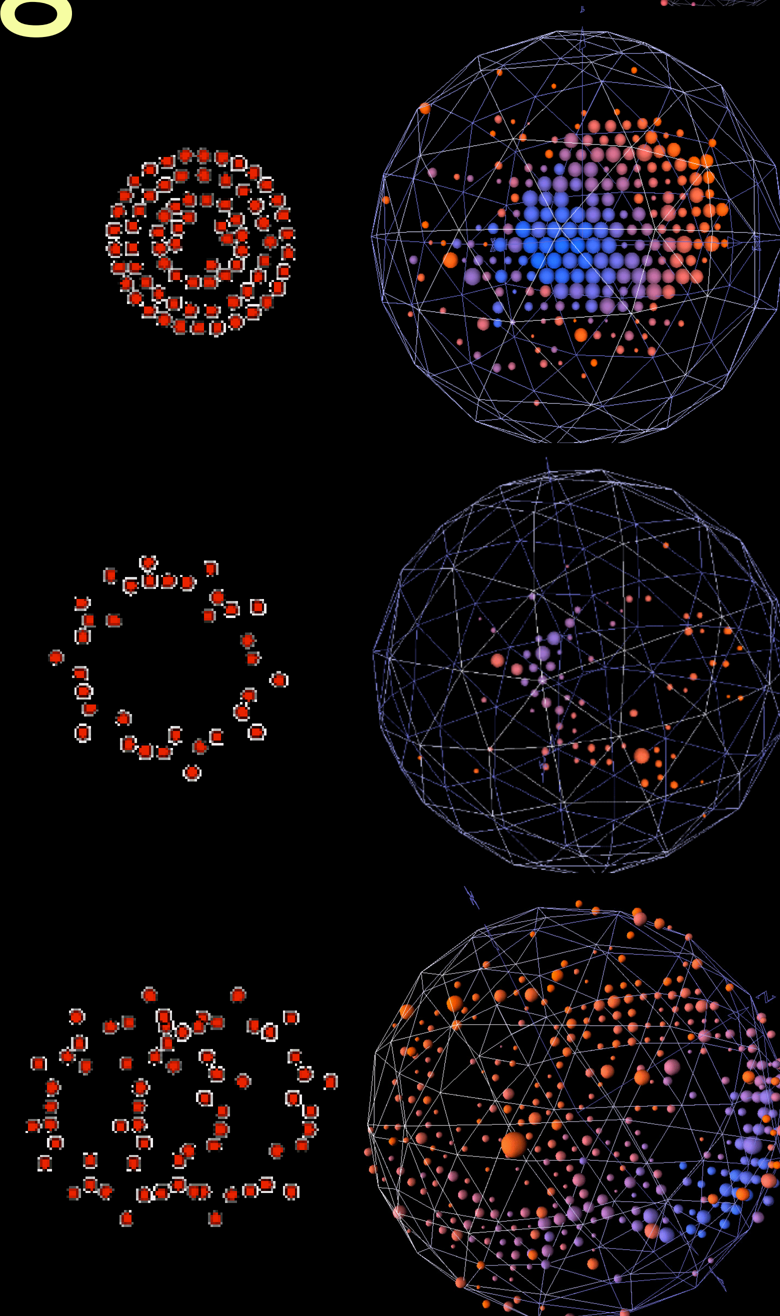
Track Images

- Muons
  - full rings
- Electrons
  - fuzzy rings
- Neutral pions
  - double rings

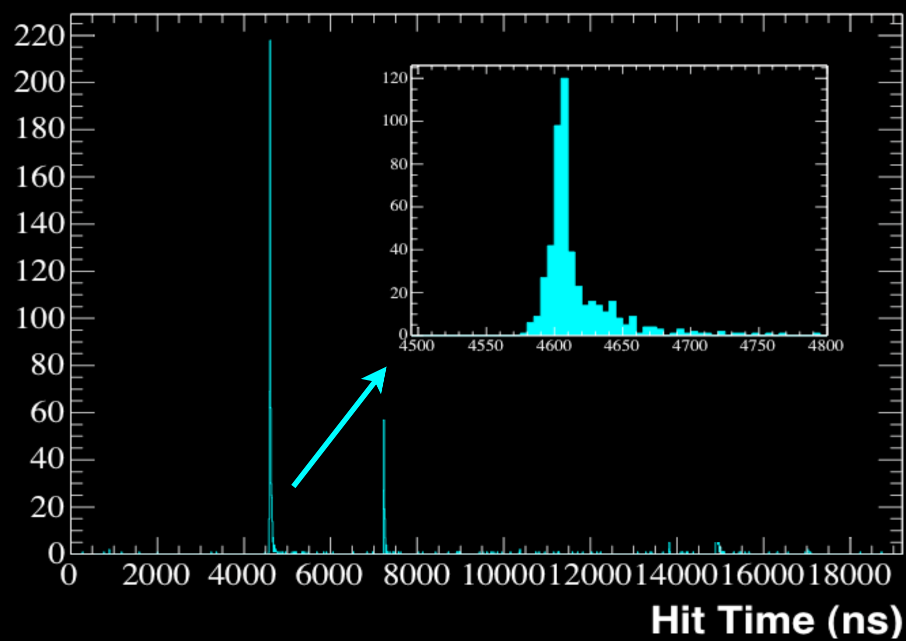


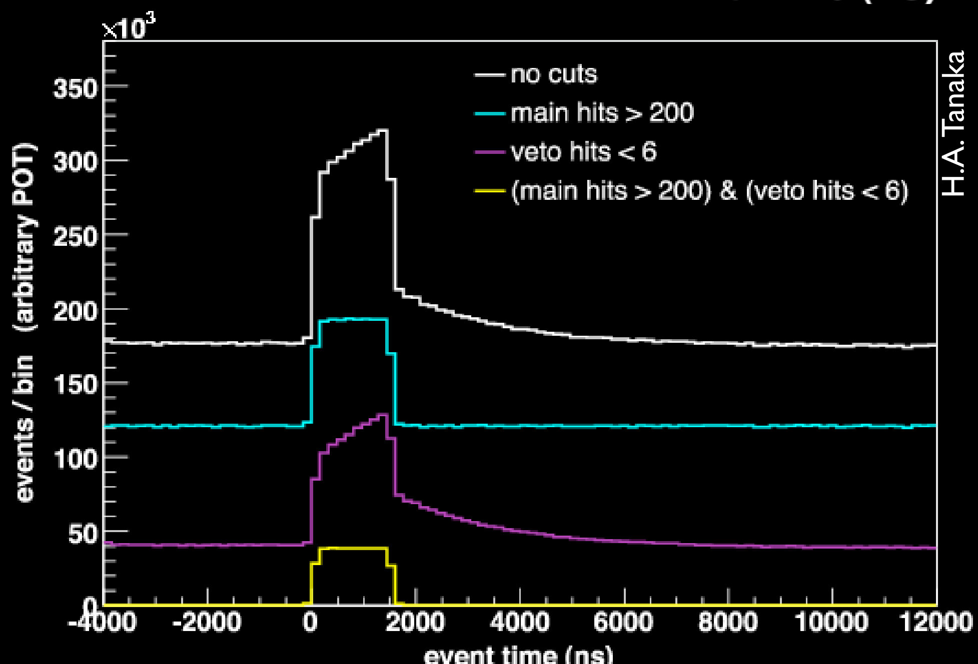






PMT Hit Clusters





- PMT hits clusters in time form "subevents"
- ν_μ events have 2 subevents
  - μ, followed by e
- ν_e events have 1 subevent
- Simple cuts on subevents remove cosmic backgrounds
  - "pre-cuts"

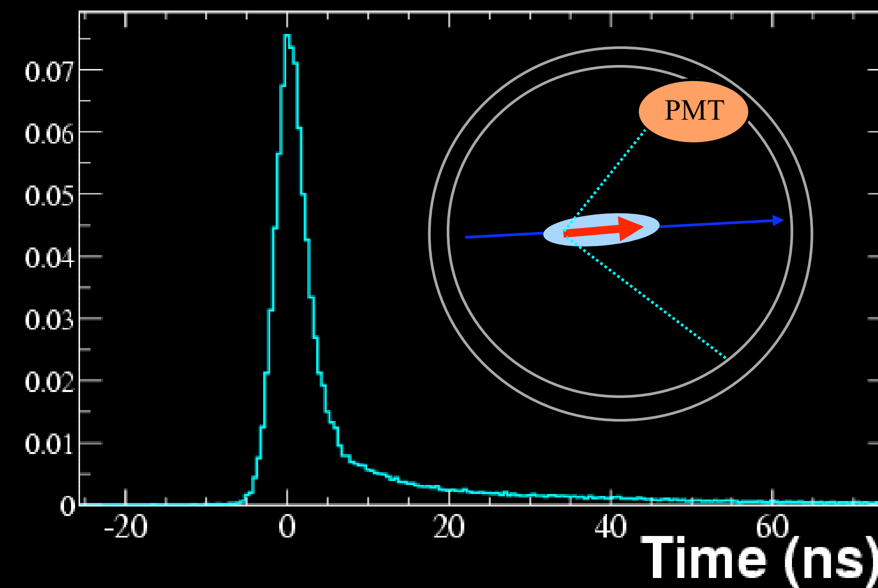
Track Reconstruction

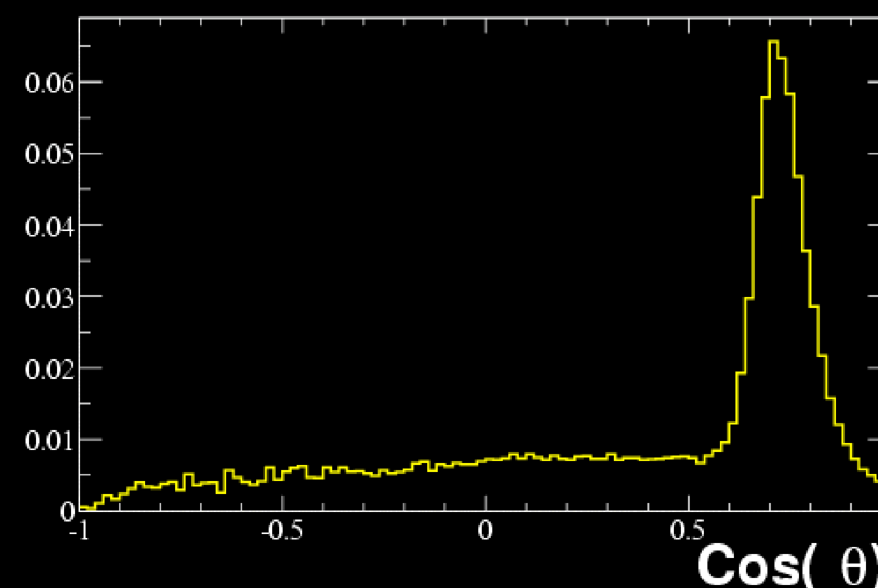
Charged particles produce Cherenkov and scintillation light in oil

PMTs collect photons, record t,Q

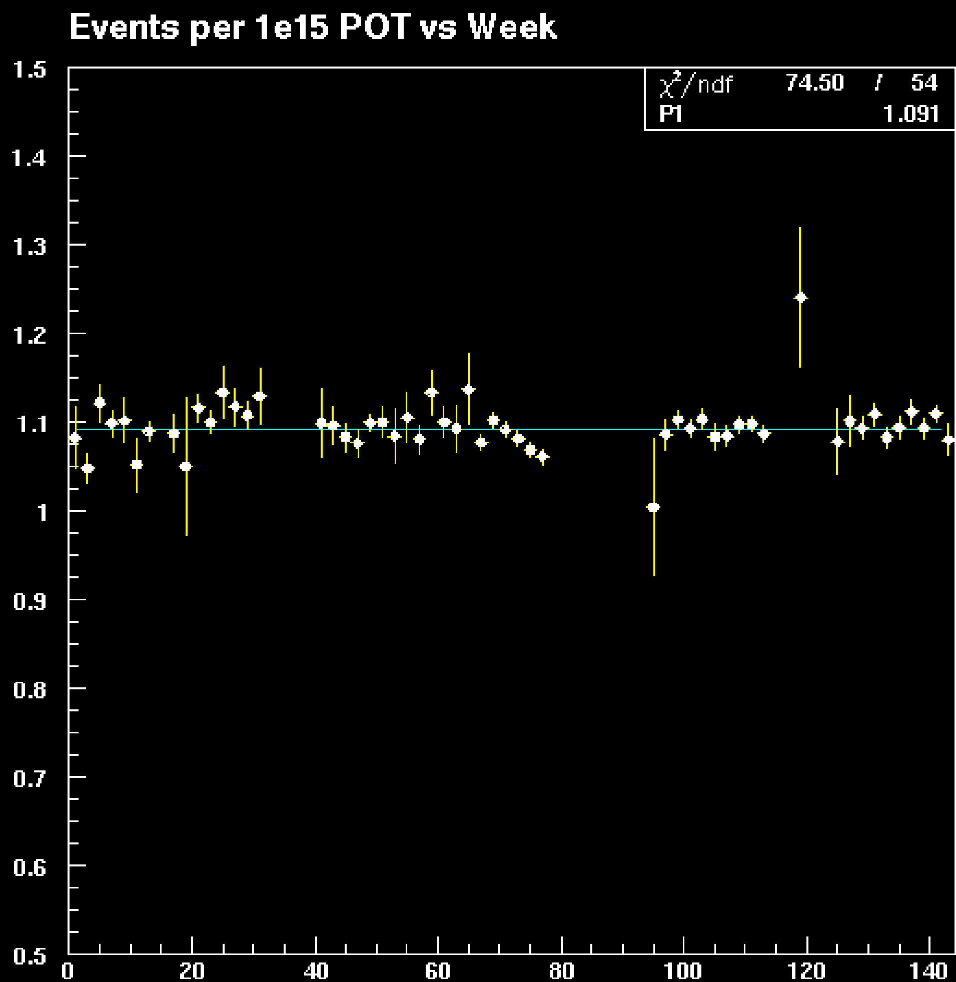
Reconstruct tracks by fitting time and angular distributions

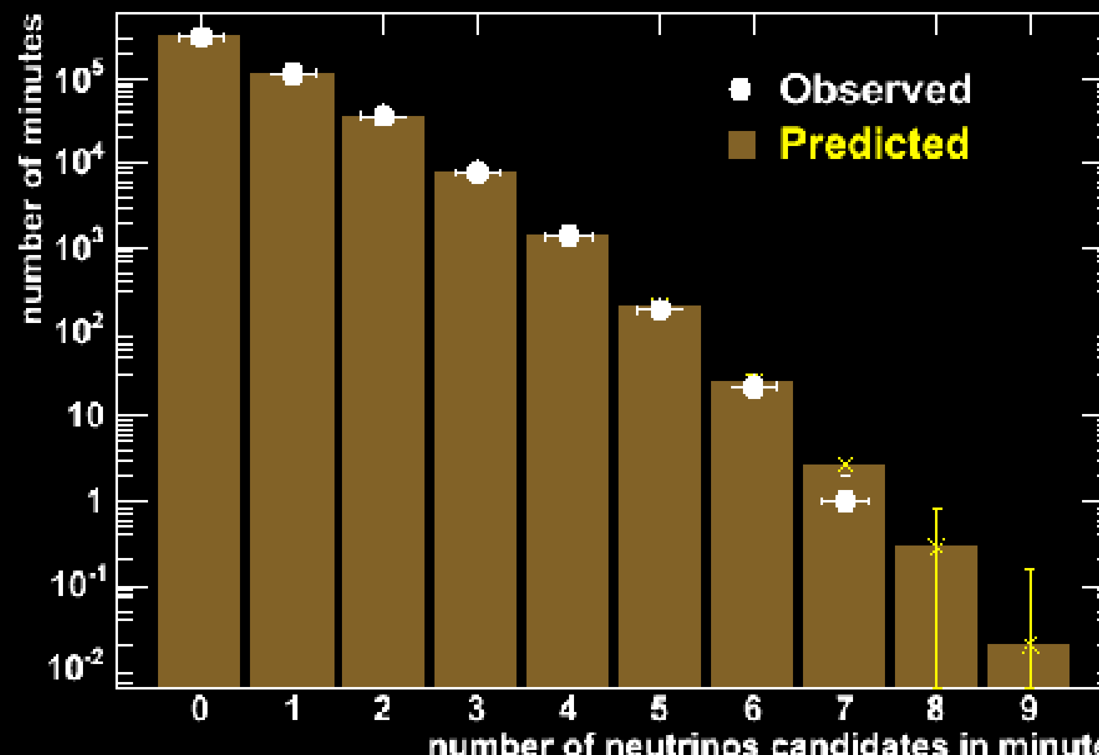
Find position, direction, energy





Detector Stability





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    1. Signal and Backgrounds
    2. Strategy
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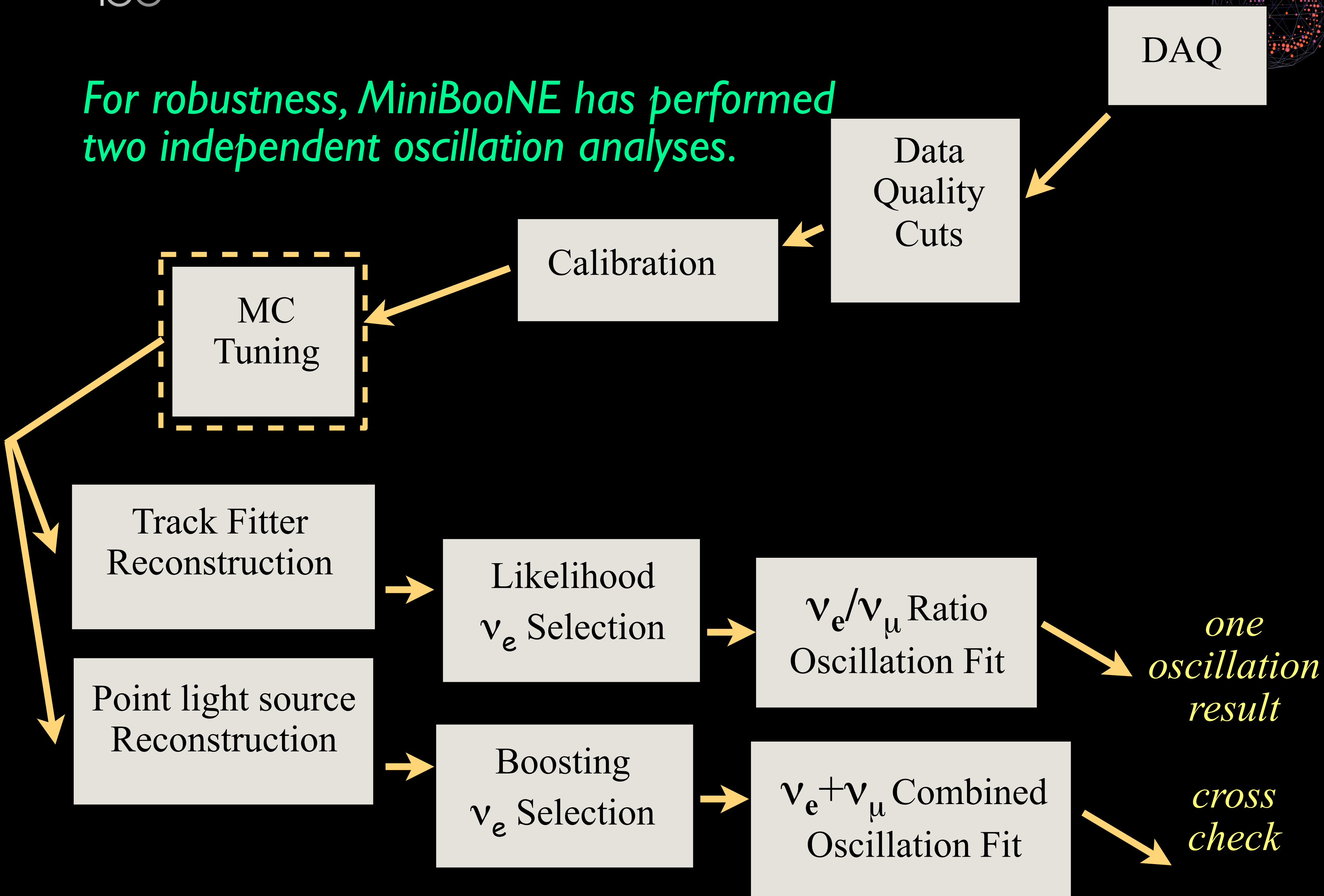
Blind Analysis

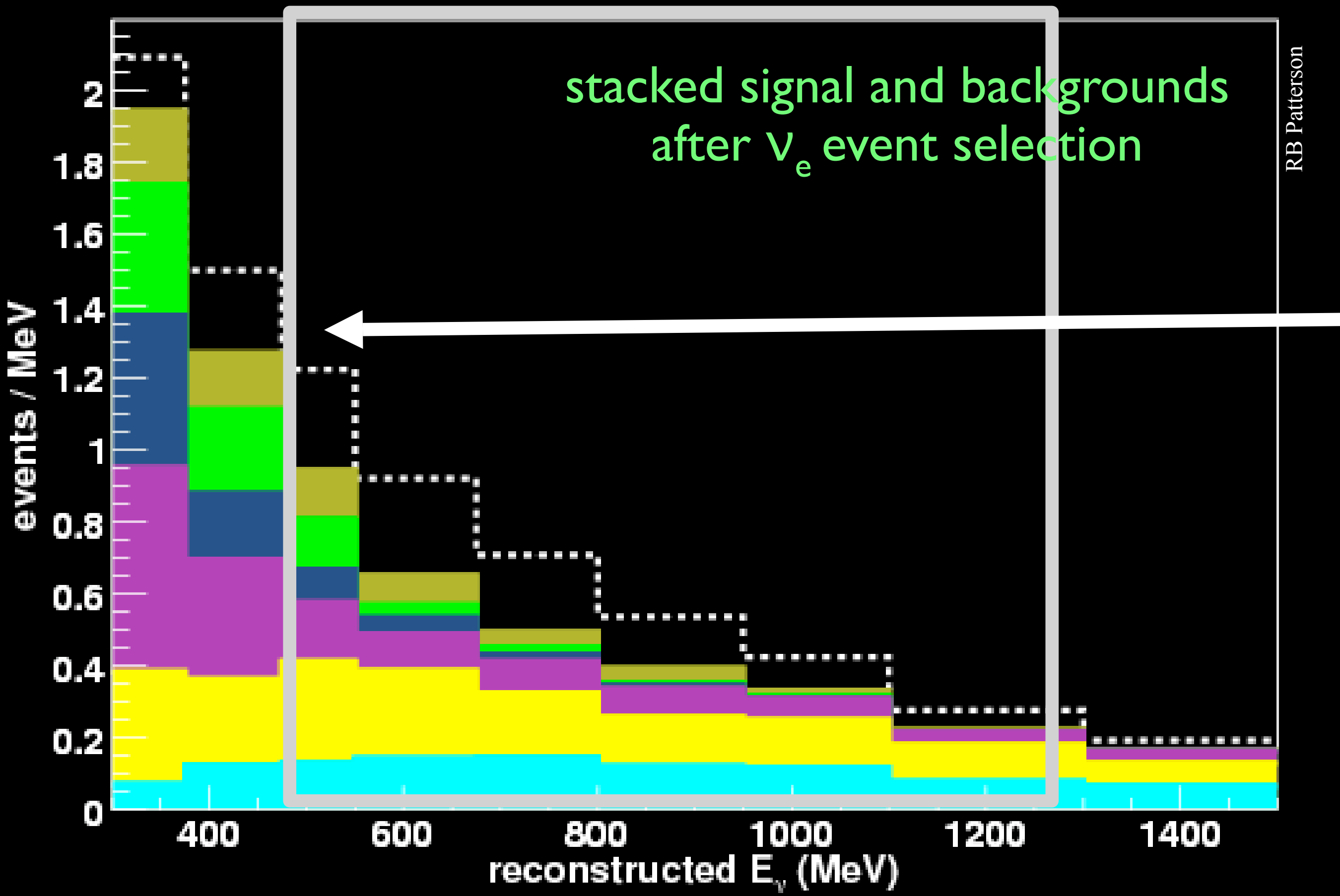
Opened specific boxes with $<1\sigma$ ν_e signal	
Initial Open Box	**Use**
all non-beam-trigger data	calibration and MC tuning
0.25% random trigger	unbiased data studies
ν_μ CCQE	measure flux, E_ν^{QE}, oscillation fit
ν_μ NCpi0	measure rate for MC tuning
ν_μ CC1pi+	check rate for MC
ν_μ-e elastic	check MC rate
"dirt"	measure MC rate
all events with $E_\nu > 1.4$ GeV	check MC rate

Second Step	
One closed signal box	explicitly sequester signal, 99% of data open

For robustness, MiniBooNE has performed two independent oscillation analyses.



Signal and Backgrounds



Oscillation ν_e

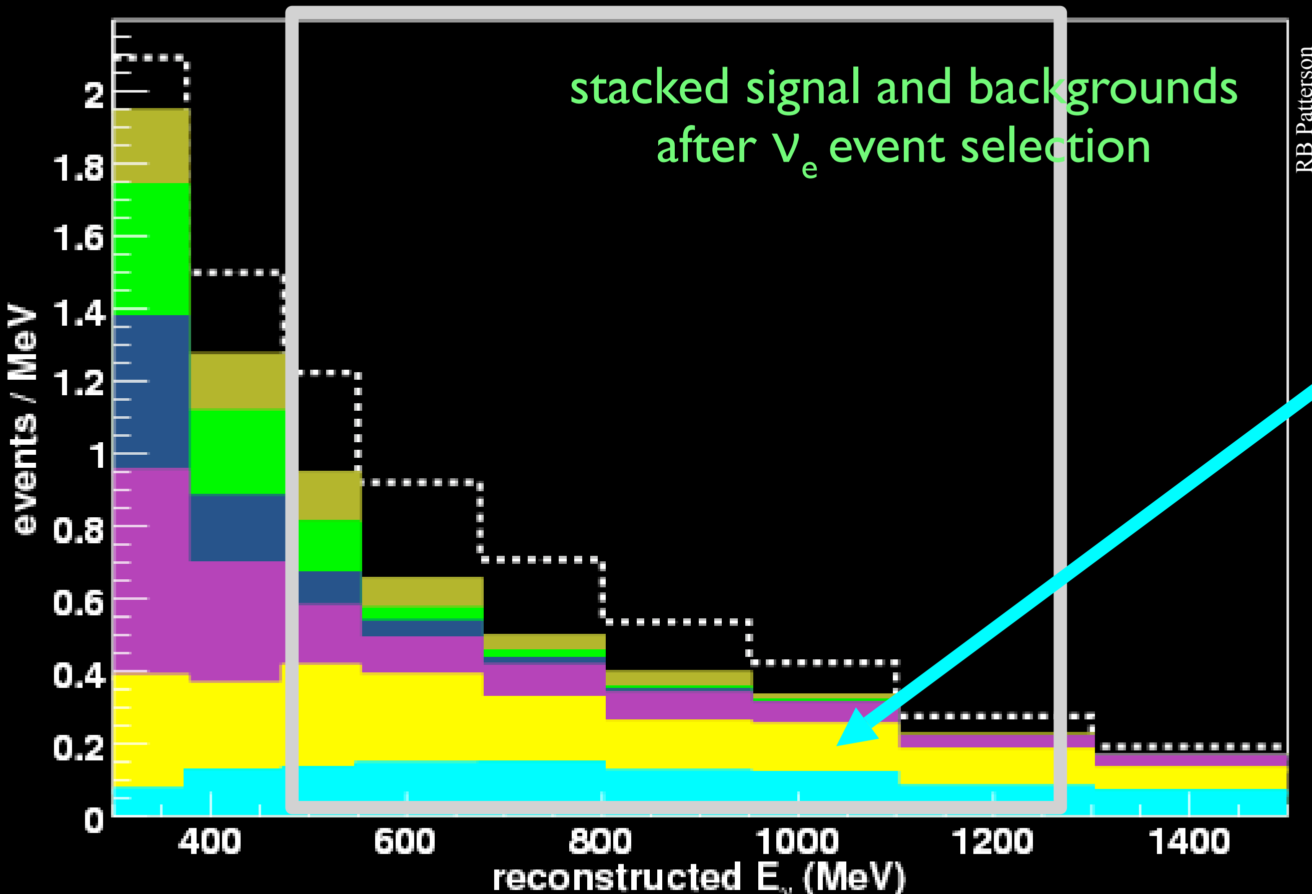
Example oscillation signal

Δm^2 = 1.2 eV^2

$SIN^2 2\theta$ = 0.003

Fit for excess as a function of reconstructed ν_e energy

Signal and Backgrounds

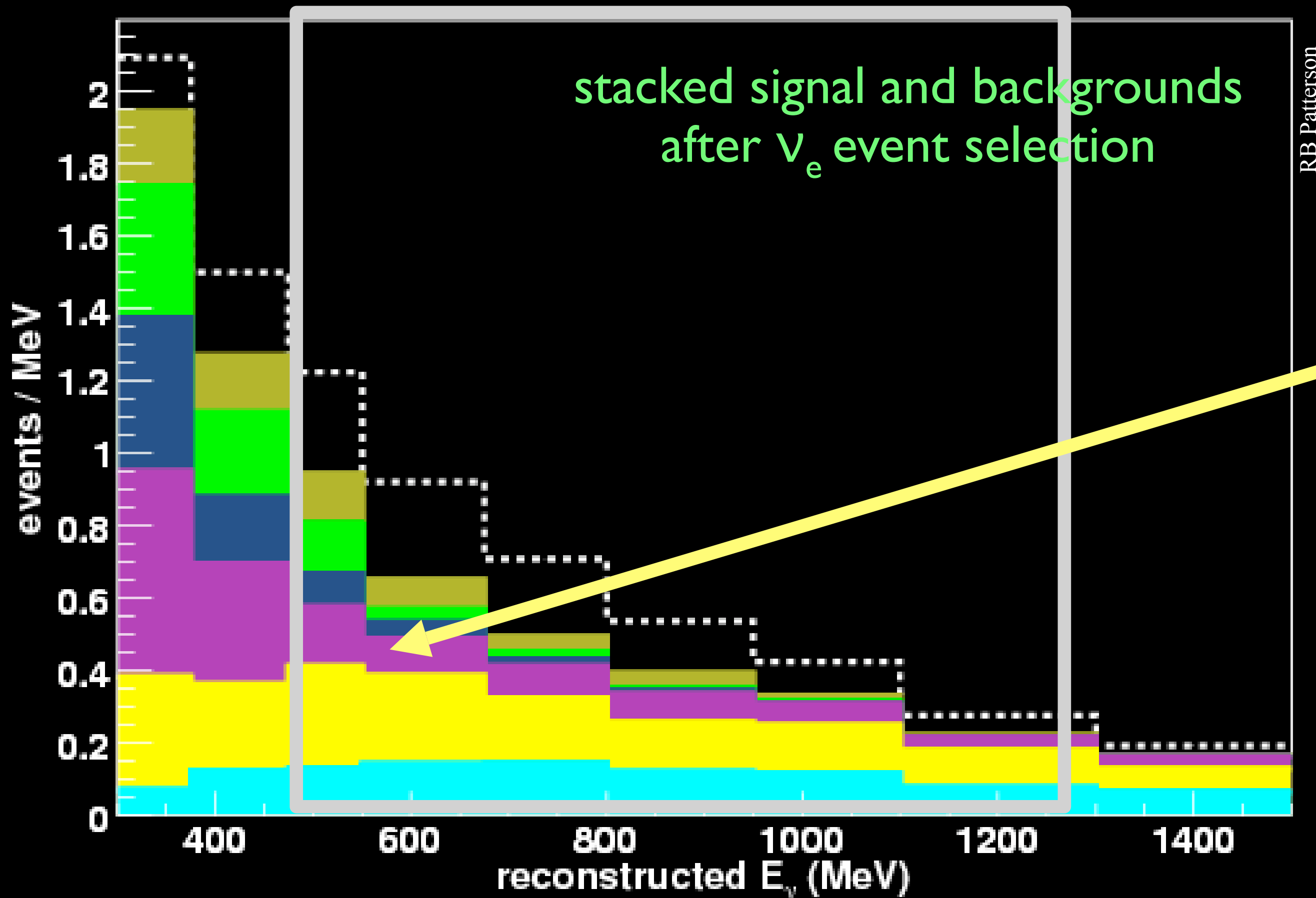


ν_e from K^+ and K^0

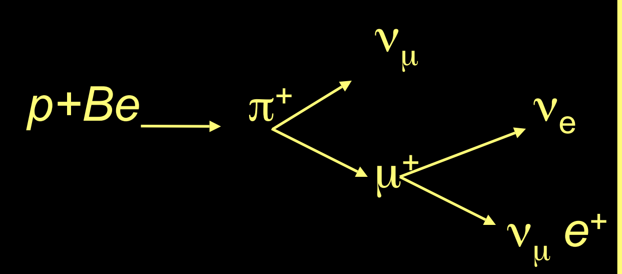
Use fit to kaon production data for shape

Use high energy ν_e and ν_μ in-situ data for normalisation cross-check

Signal and Backgrounds

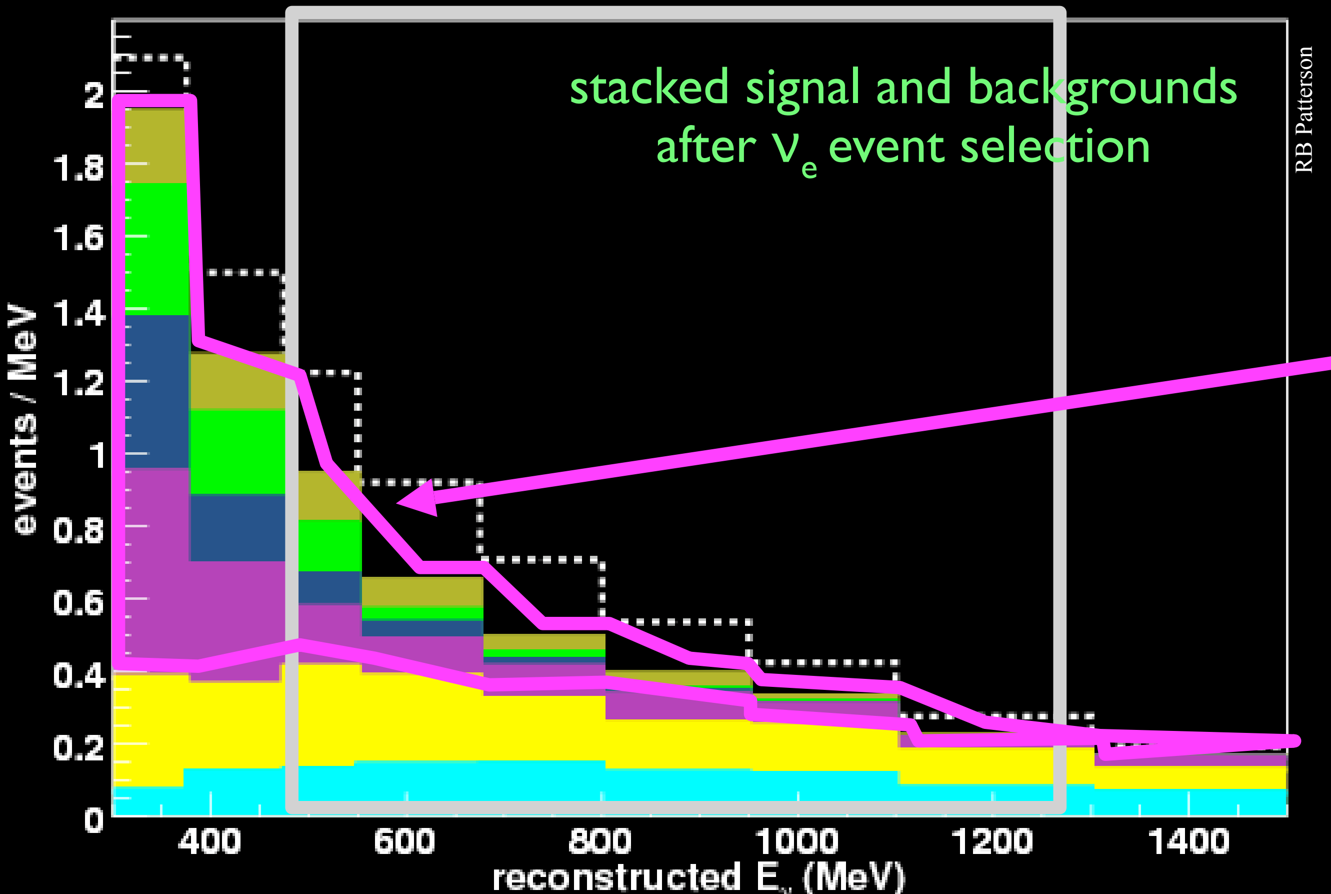


ν_e from μ^+



- Measured with in-situ ν_μ CCQE sample
  - Same ancestor π^+ kinematics
- Most important background
  - Constrained to a few %

Signal and Backgrounds



MisID ν_μ

~46% π^0

Determined by clean π^0 measurement

~16% Δ γ decay

π^0 measurement constrains

~14% "dirt"

Measure rate to normalise and use MC for shape

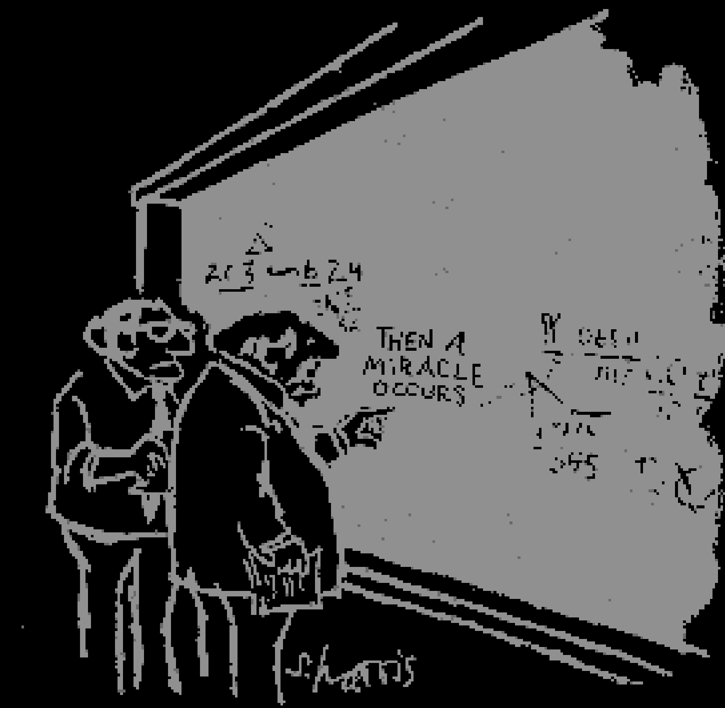
~24% other

Use ν_μ CCQE rate to normalise and MC for shape

Strategy

Incorporate in-situ data whenever possible

- MC tuning with calibration data
  - energy scale
  - PMT response
  - optical model
- MC tuning with neutrino data
  - cross section nuclear model parameters
  - π^0 rate constraint
- Constraining systematic errors with neutrino data
  - ratio method: ν_e from μ decay
  - combined fit to ν_e and ν_μ data



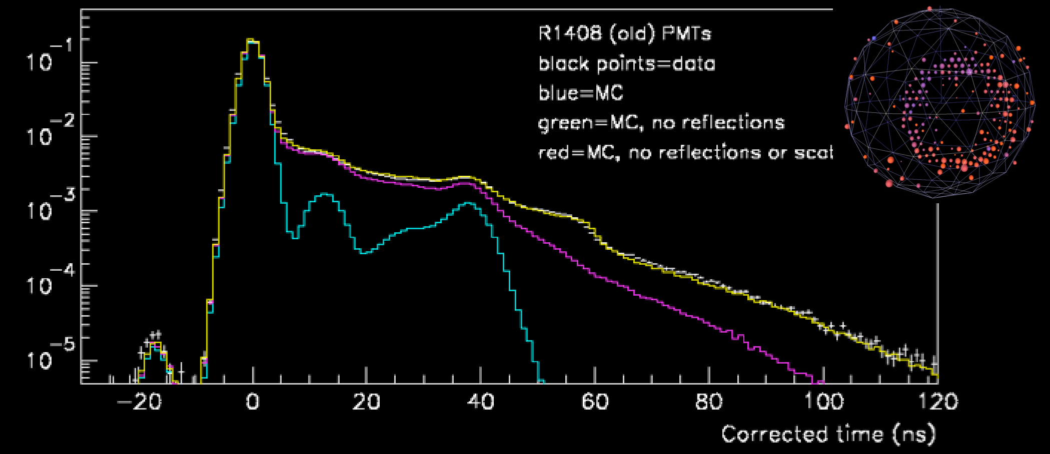
"I think you should be more explicit here in step two."

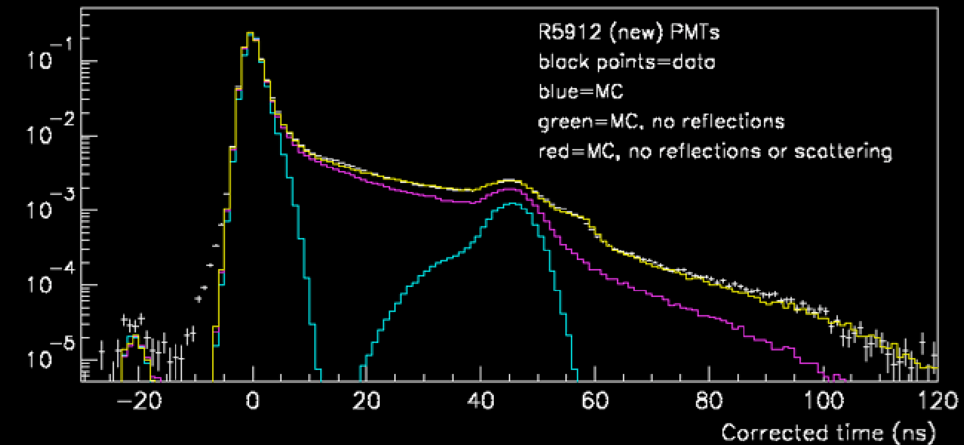
Recurring theme:
good data-MC agreement

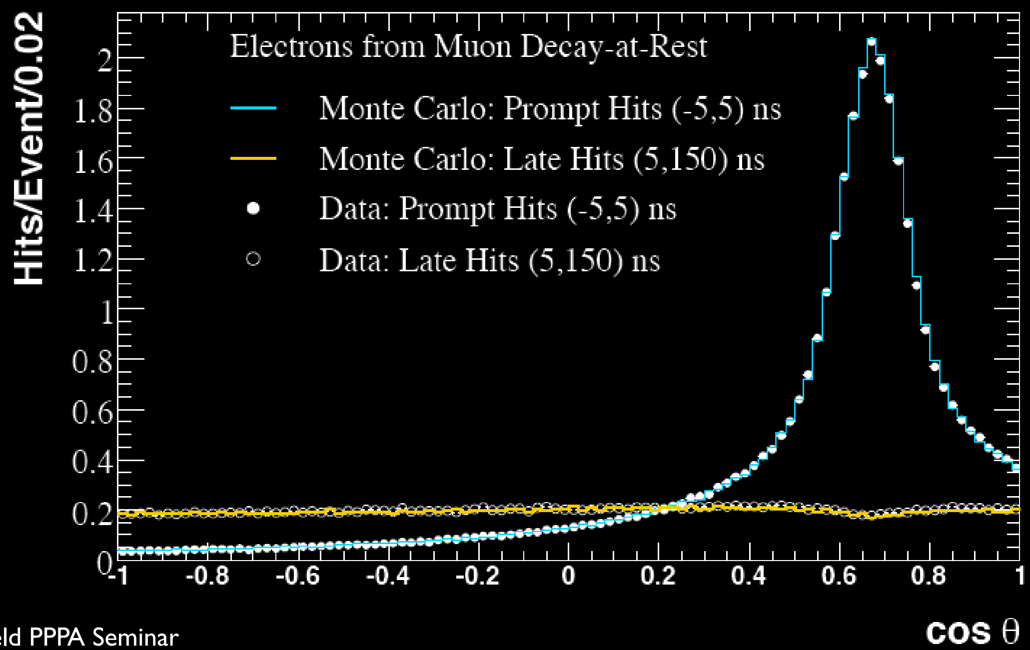
MC Tuning

Good data/MC agreement

- Basic PMT hit distributions showing details of optical model
- Aggregate PMT hit distributions showing gross detector behaviour







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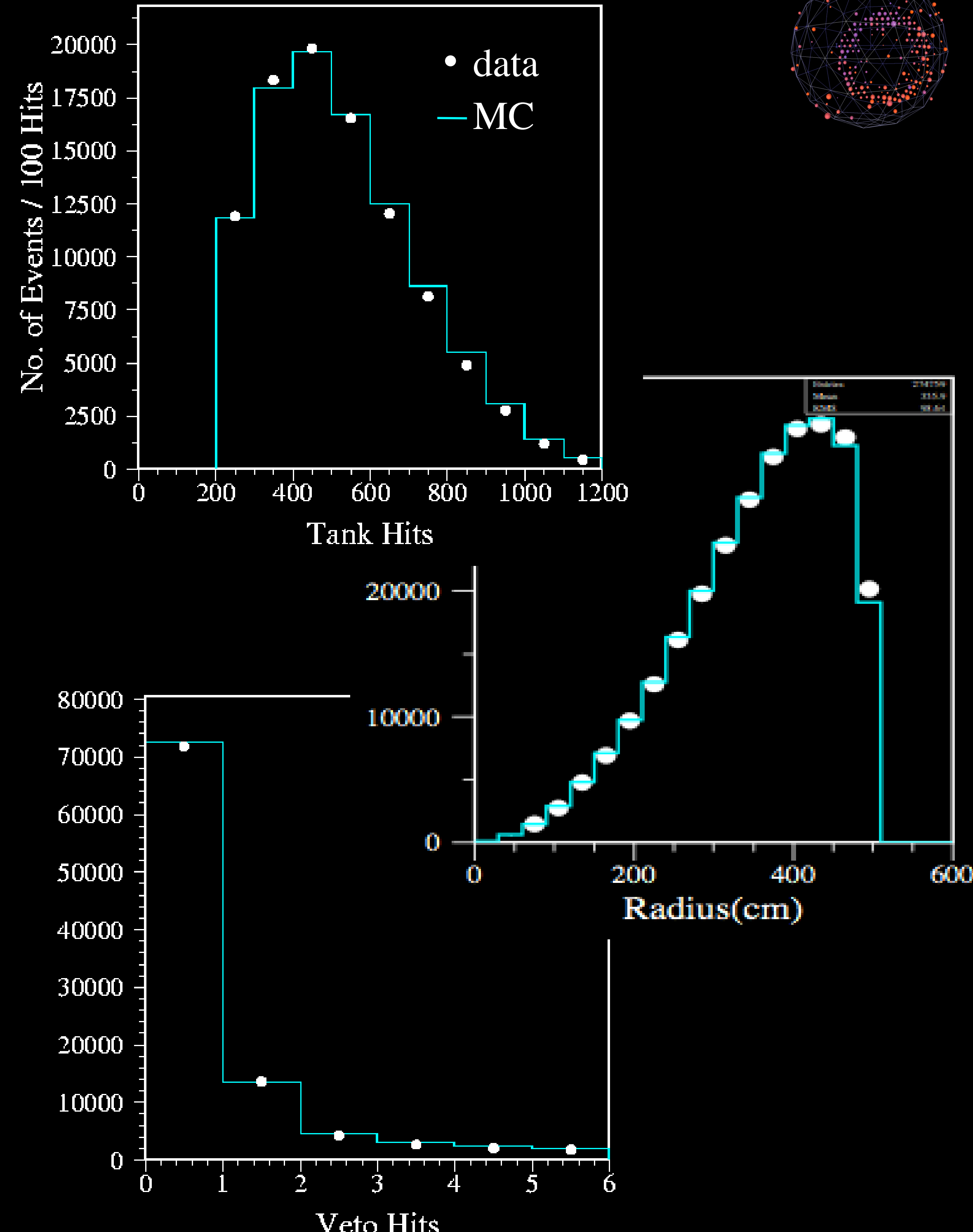

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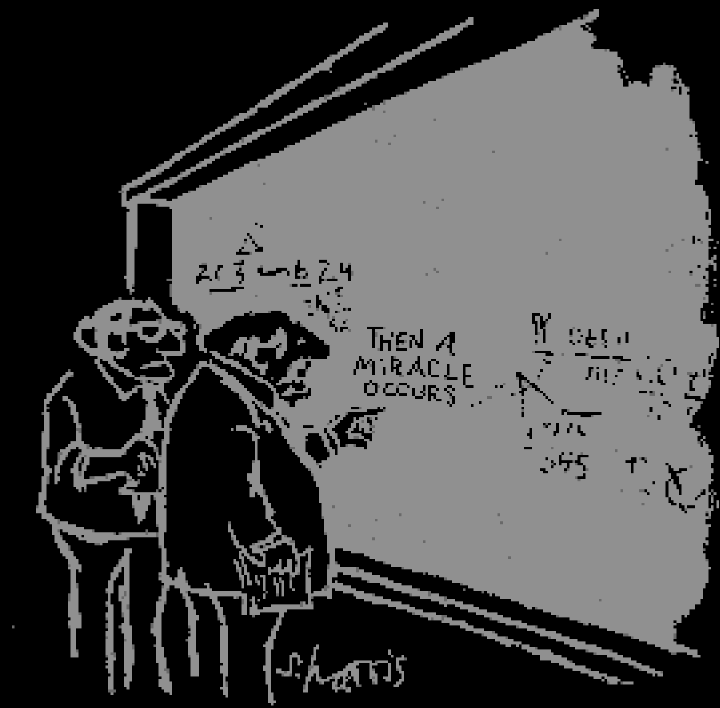

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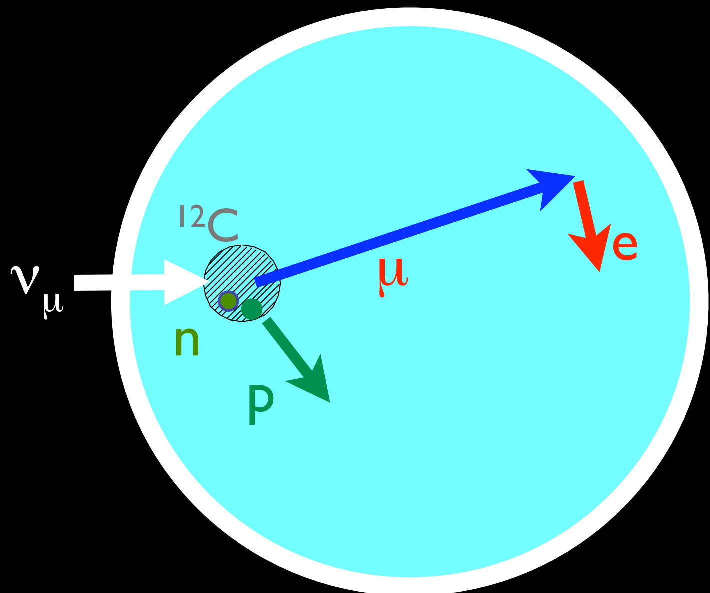
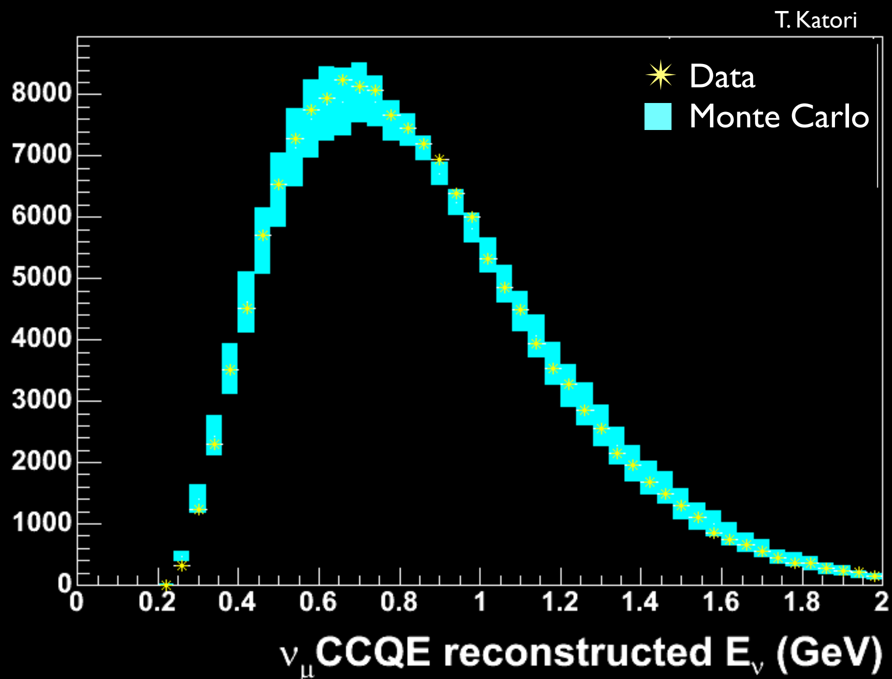
ν_μ CCQE events

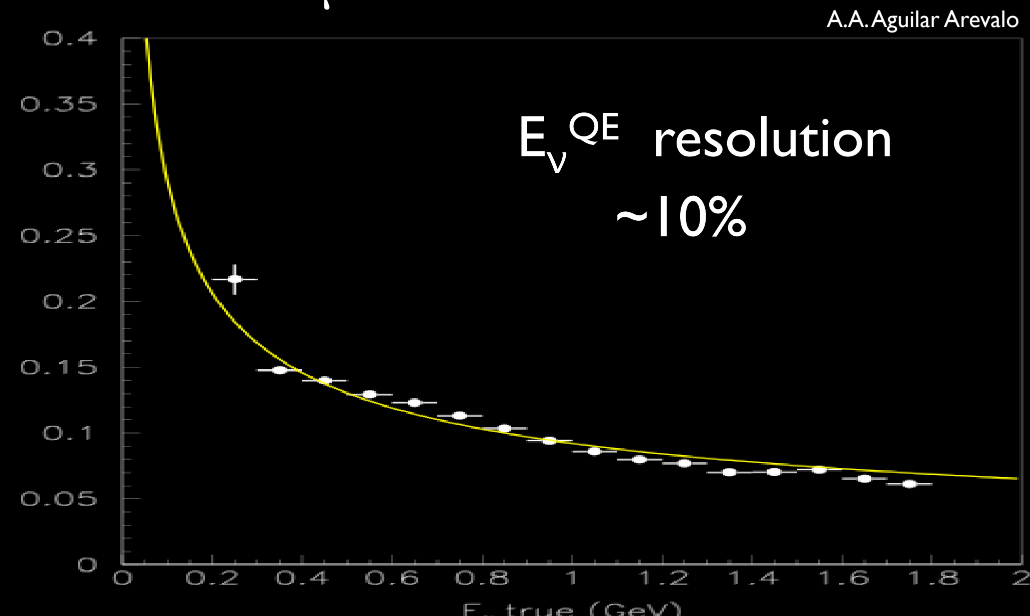


Used to measure flux and check E_ν^{QE} reconstruction

$$E_\nu^{QE} = \frac{1}{2}\frac{2M_p E_\mu - m_\mu^2}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\cos\theta_\mu}$$

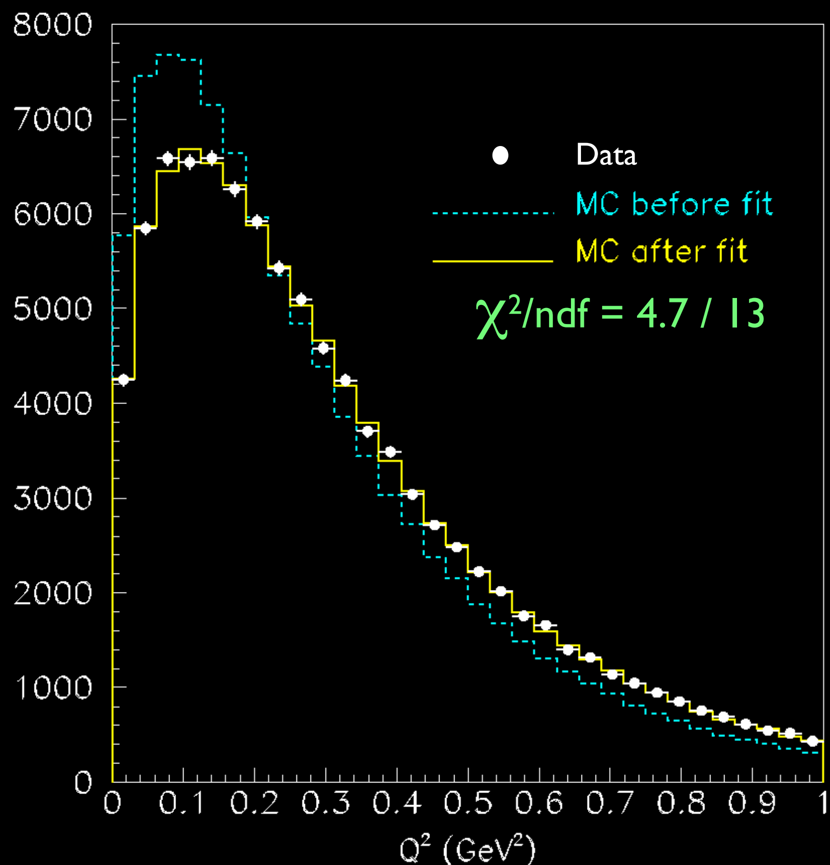
- 2 subevents: e, μ
  - Require e be located near end of μ track

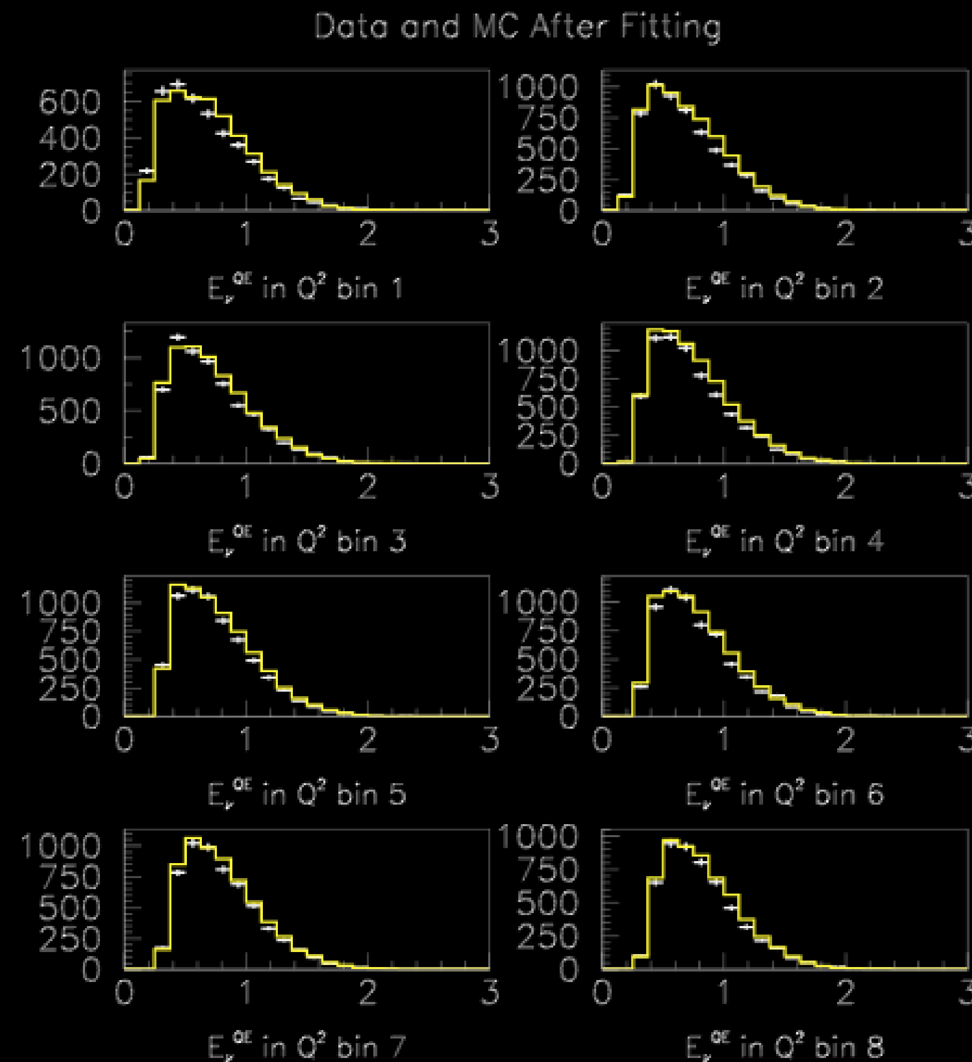




Tuning CCQE MC

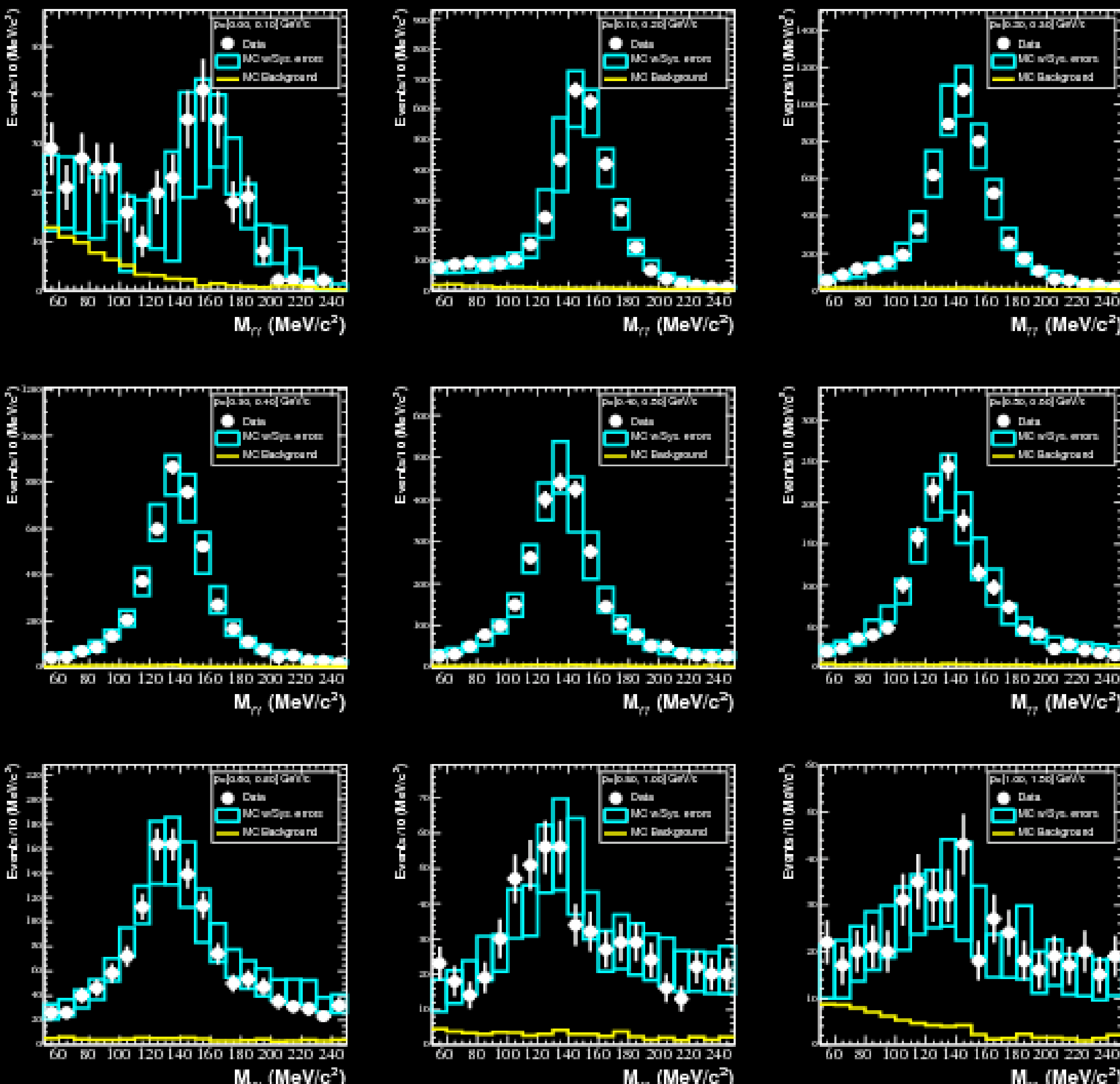
Q^2 distribution fit to tune empirical parameters of nuclear model (^{12}C)

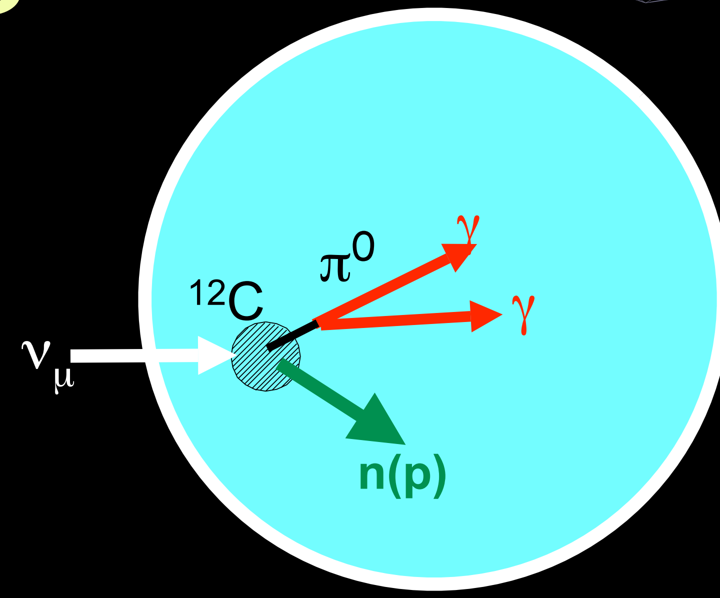




good data-MC agreement in variables not used in tuning!

π^0 Mis-ID Backgrounds

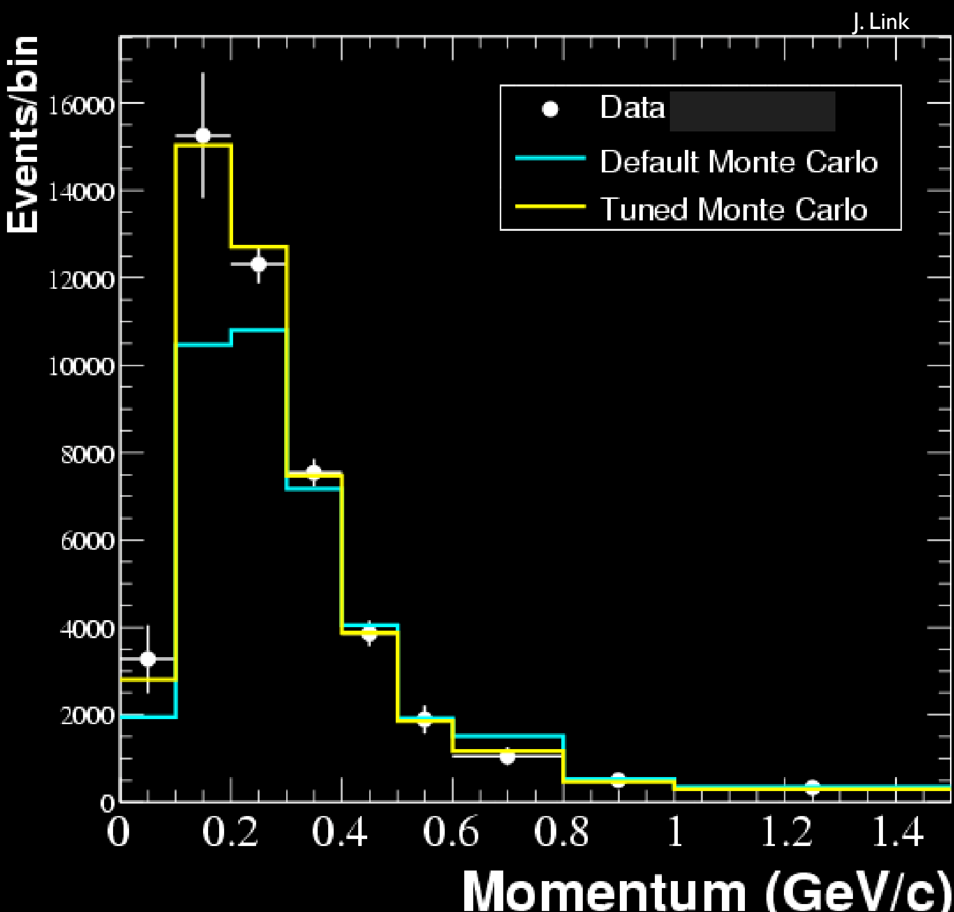


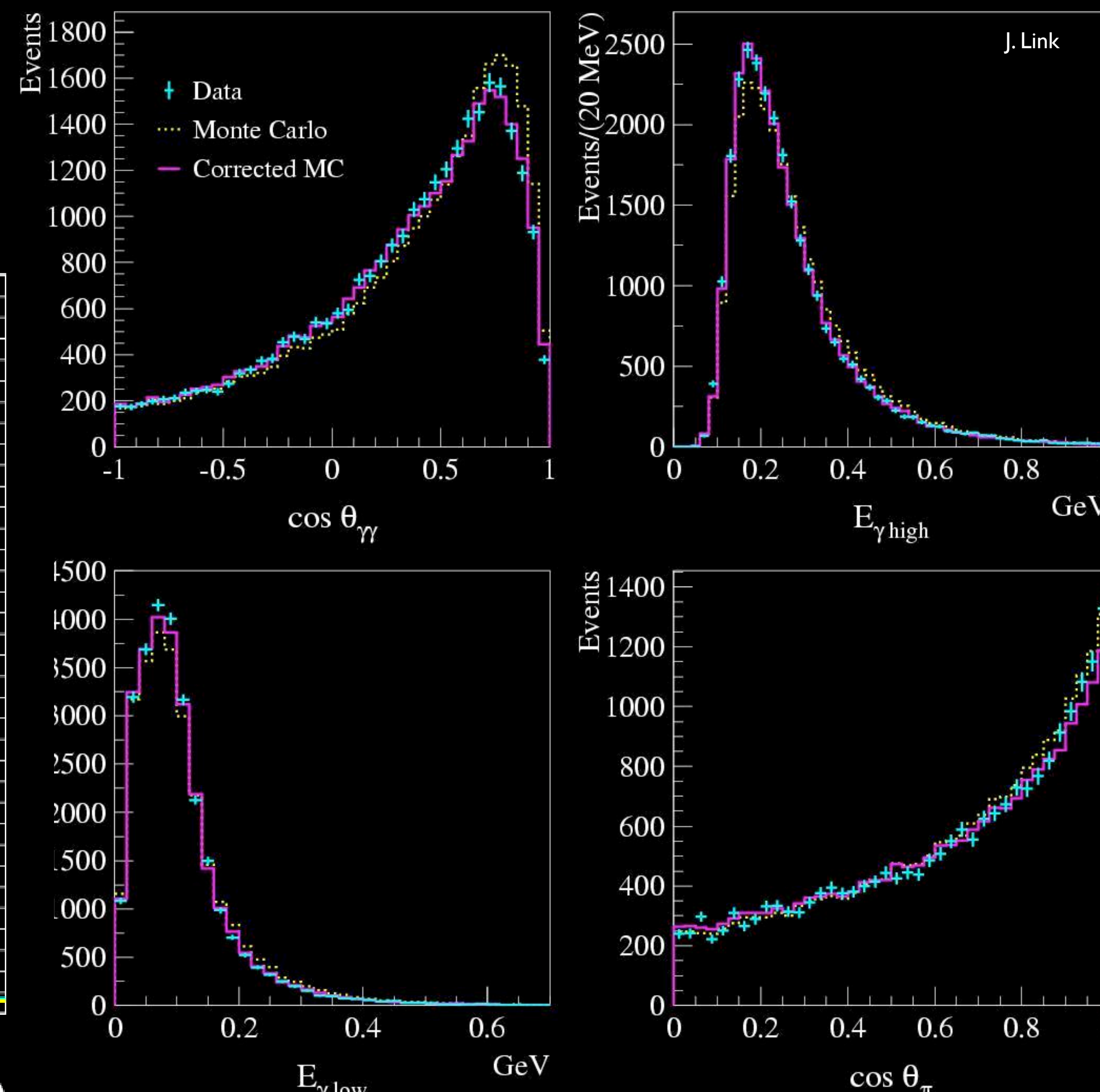


- π^0s are reconstructed outside mass peak if:
  - asymmetric decays fake 1-ring
  - 1 of 2 photons exits
  - high momentum π^0 decays produce overlapping rings

Tuning π^0 MC

The MC π^0 rate (flux × xsec) is re-weighted to match the measurement in p_π bins.



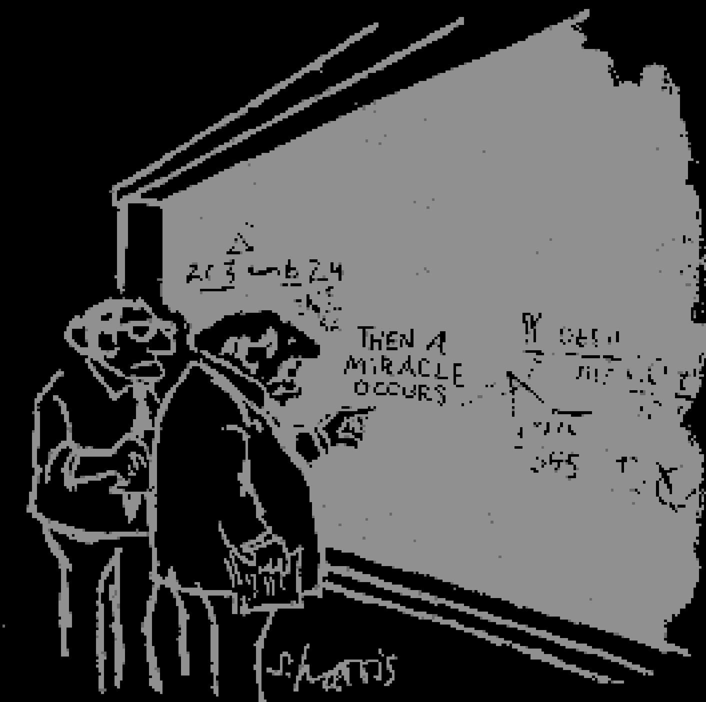


good data-MC agreement in variables not used in tuning!

Strategy

Incorporate in-situ data whenever possible

- MC tuning with calibration data
  - energy scale
  - PMT response
  - optical model
- MC tuning with neutrino data
  - cross section nuclear model parameters
  - π^0 rate constraint
- Constraining systematic errors with neutrino data
  - ratio method: ν_e from μ decay
  - combined fit to ν_e and ν_μ data



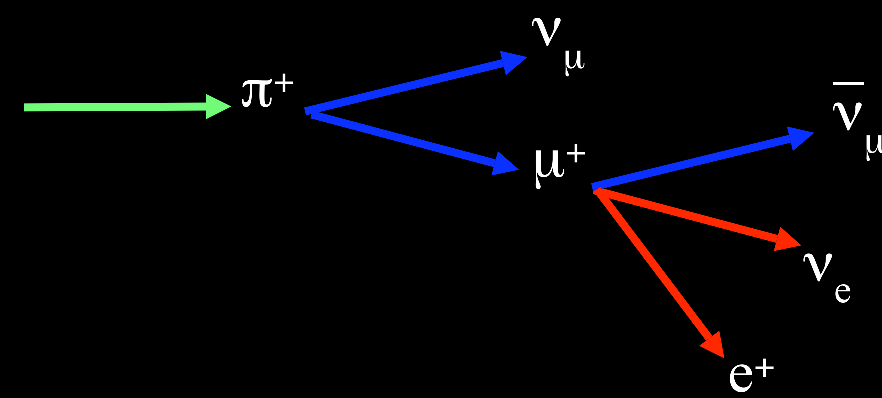
"I think you should be more explicit here in step two."

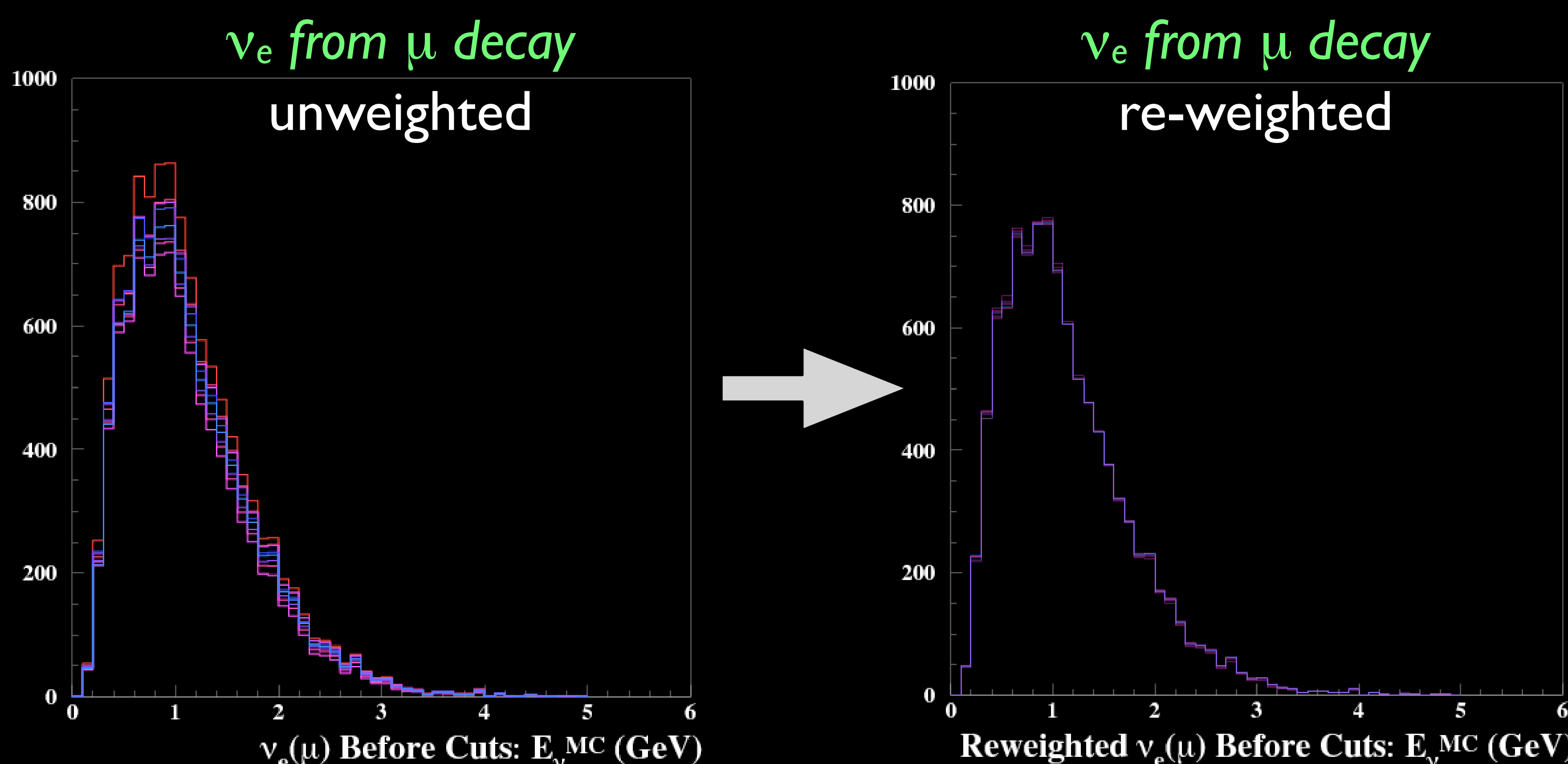
Recurring theme:
good data-MC agreement

Analysis Strategy 1:

Ratio Method

- MC predicts a range of ν_μ fluxes
- Use data/MC ratio of ν_μ CCQE events to re-weight parent π^+





Analysis Strategy 2:

Combined Fit

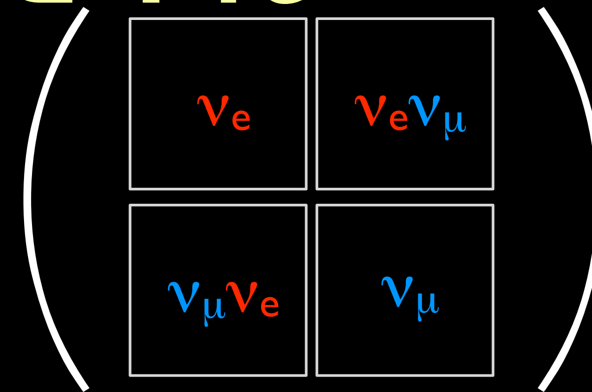
- For each Eν bin i,

$$\Delta_i = N_i^{DATA} - N_i^{MC}$$

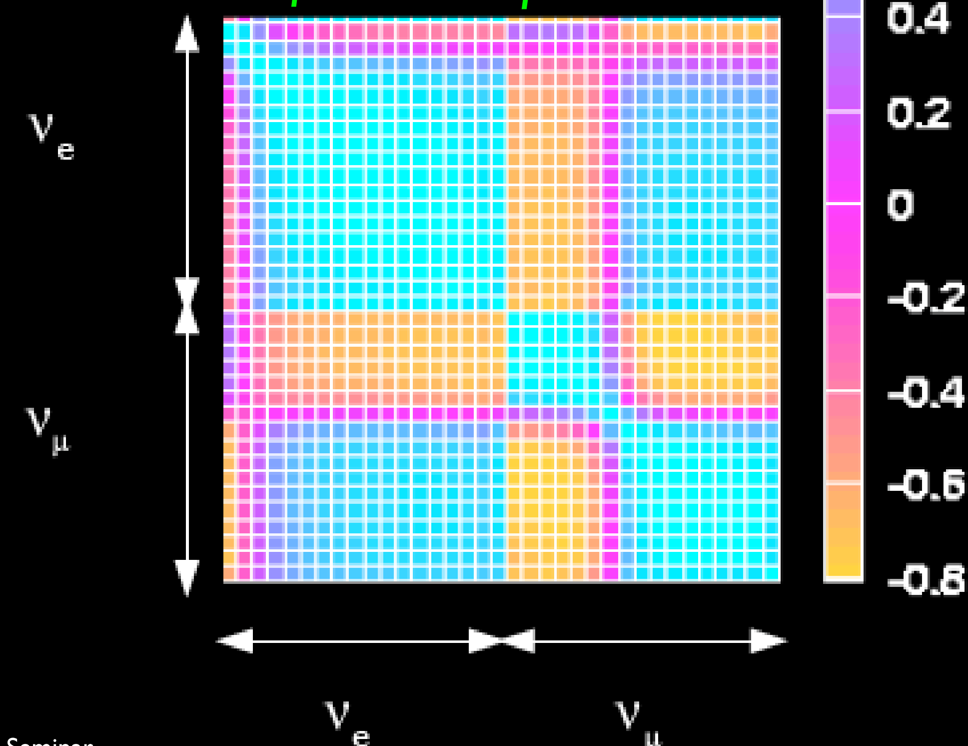
- Raster-scan in Δm^2 and $\sin^2 2\theta_{\mu e}$ to calculate χ^2 over ν_e and ν_μ bins

$$\chi^2 = \sum_{i=1}^{N_{bins}} \sum_{j=1}^{N_{bins}} \Delta_i \mathcal{M}_{ij}^{-1} \Delta_j$$

- Systematic error matrix includes uncertainties for ν_e and ν_μ



Correlations between E_ν^{QE} bins from the optical model:

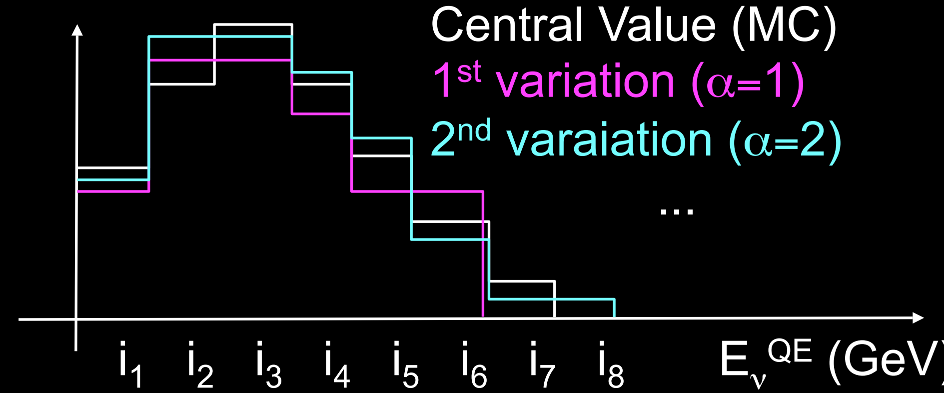


Error Matrix

$$\mathcal{M}_{ij} = \frac{1}{N_\alpha} \sum_{\alpha=1}^{N_\alpha} (N_i^\alpha - N_i^{MC})(N_j^\alpha - N_j^{MC})$$

- Use MC variations to study systematic uncertainties
- Vary underlying parameters and compare to “central value” MC
- Total error matrix is sum of individual matrices

Example of Eν distributions for several MC variations



Systematic Errors

	constraint?
Neutrino flux predictions	
meson production cross sections	✓
meson secondary interactions	✓
focussing horn current	
target and horn system alignment	
Neutrino interaction cross sections	
nuclear model	✓
rates and kinematics for relevant processes	✓
resonance width and branching fractions	✓
Detector modelling	
optical model of light propagation	✓
PMT charge and time response	✓
electronics & DAQ model	✓
neutrino interactions in dirt surrounding detector	✓

Outline

1. Motivation and Introduction
2. Description of the Experiment
3. Analysis Overview
4. Two Independent Oscillation Searches
    1. Reconstruction and Event Selection
    2. Systematic Uncertainties
5. First Results
6. Updates Since First Result

2 Independent Searches

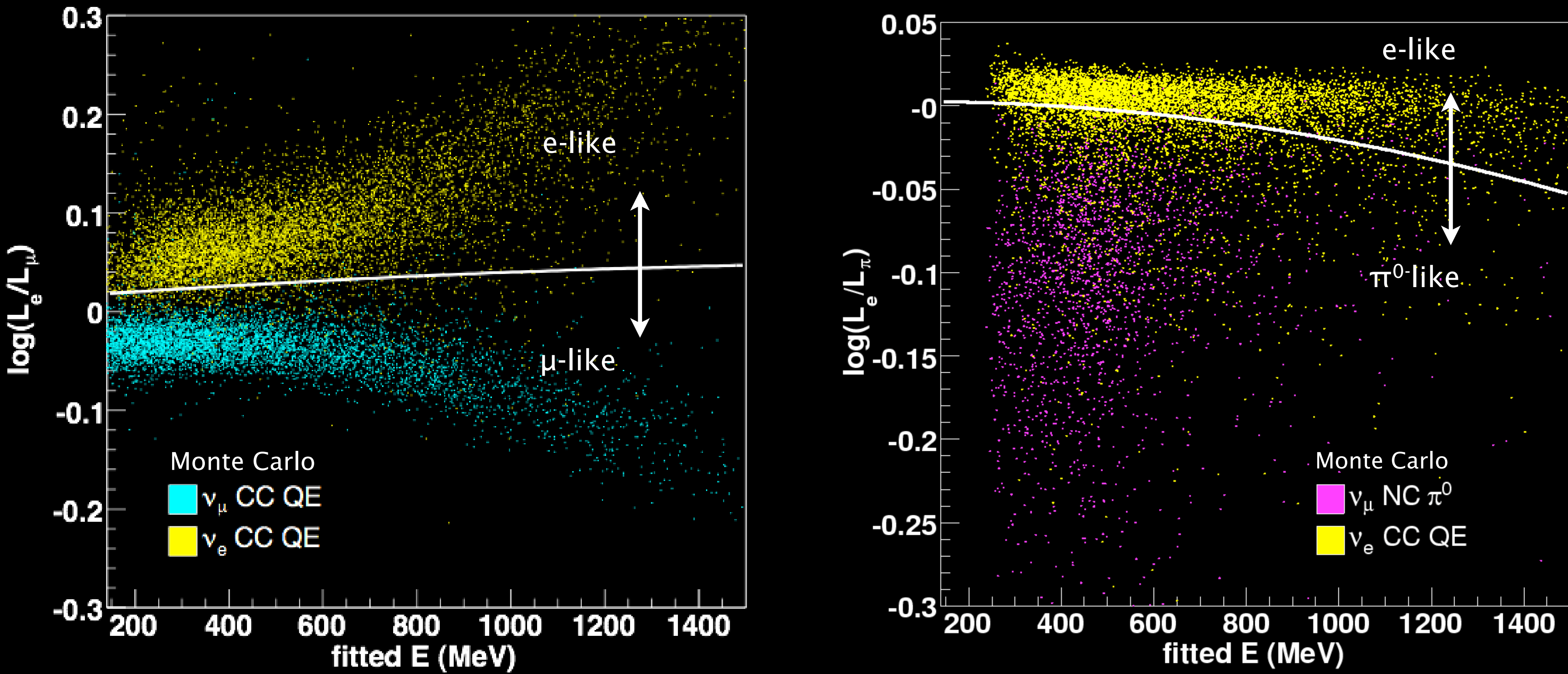
Primary Analysis

- **Method 1: Track Based Analysis**
  - Careful Reconstruction of particle tracks
  - Identify particle type by likelihood ratio
  - Use ratio method to constrain backgrounds
  - ✓ Strengths:
    - Relatively insensitive to optical model
    - Simple cuts on likelihood ratios

Cross-check Analysis

- **Method 2: Boosted Decision Trees**
  - Classify events using boosted decision trees
  - Cut on output variables to improve event separation
  - Use combined fit to constrain backgrounds
  - ✓ Strengths:
    - Combine weak variables to form strong classifier
    - Better constraints on backgrounds

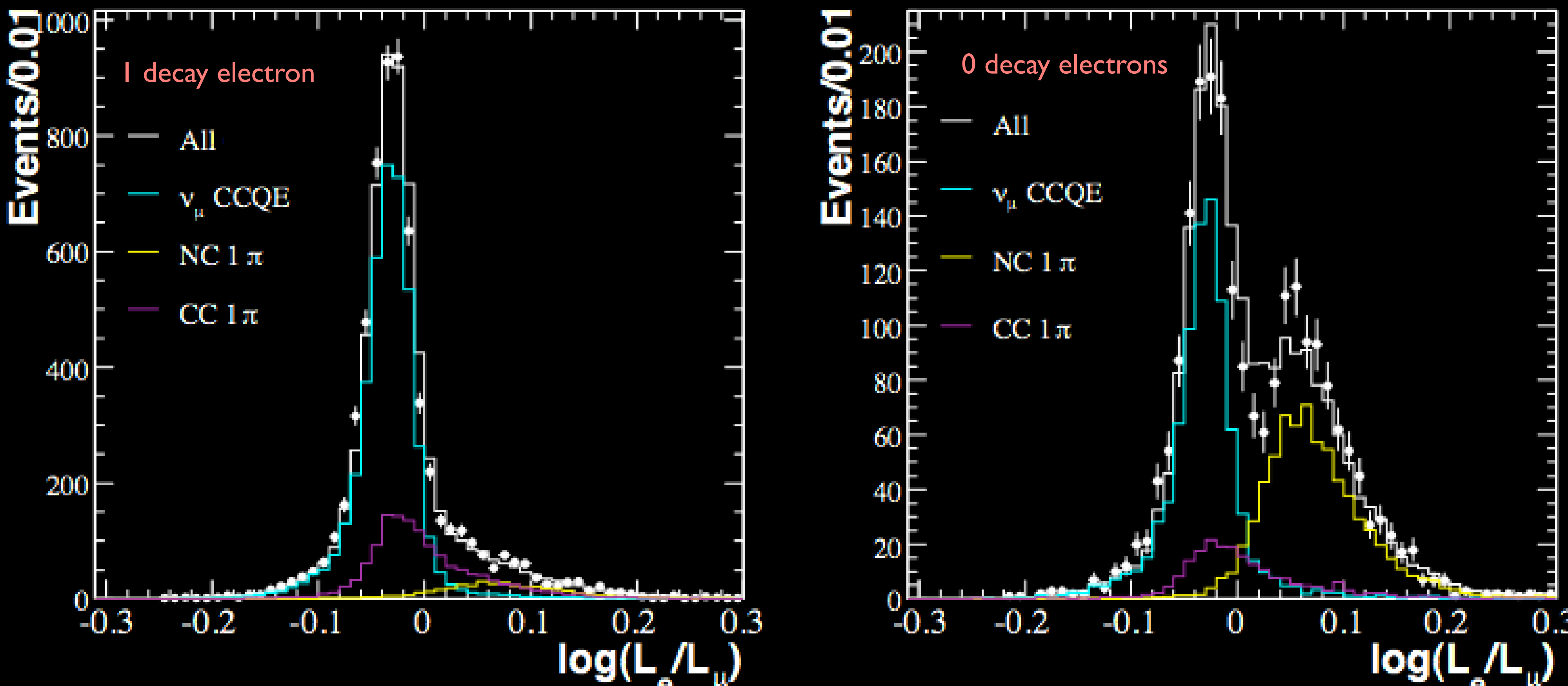
Particle Identification



- Reconstruct under 3 hypotheses: μ-like, e-like and π^0-like
- ν_e particle ID cuts on likelihood ratios
  - chosen to maximise $\nu_\mu \rightarrow \nu_e$ oscillation sensitivity

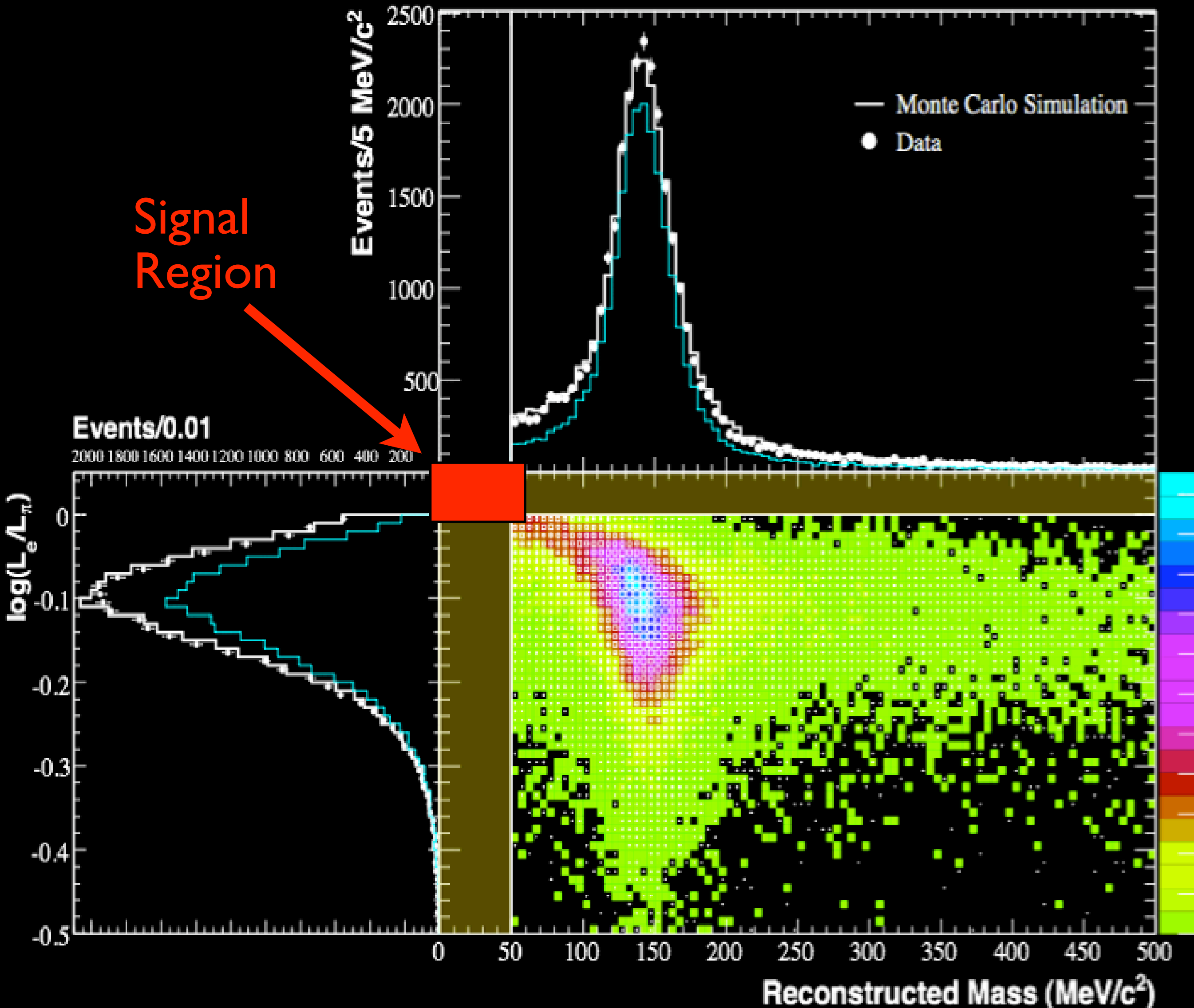
e/μ Likelihood

- ν_μ CCQE data (with muon decay electron) compared to ν_μ data with no decay electrons ("All but signal")
- Removes most muon events

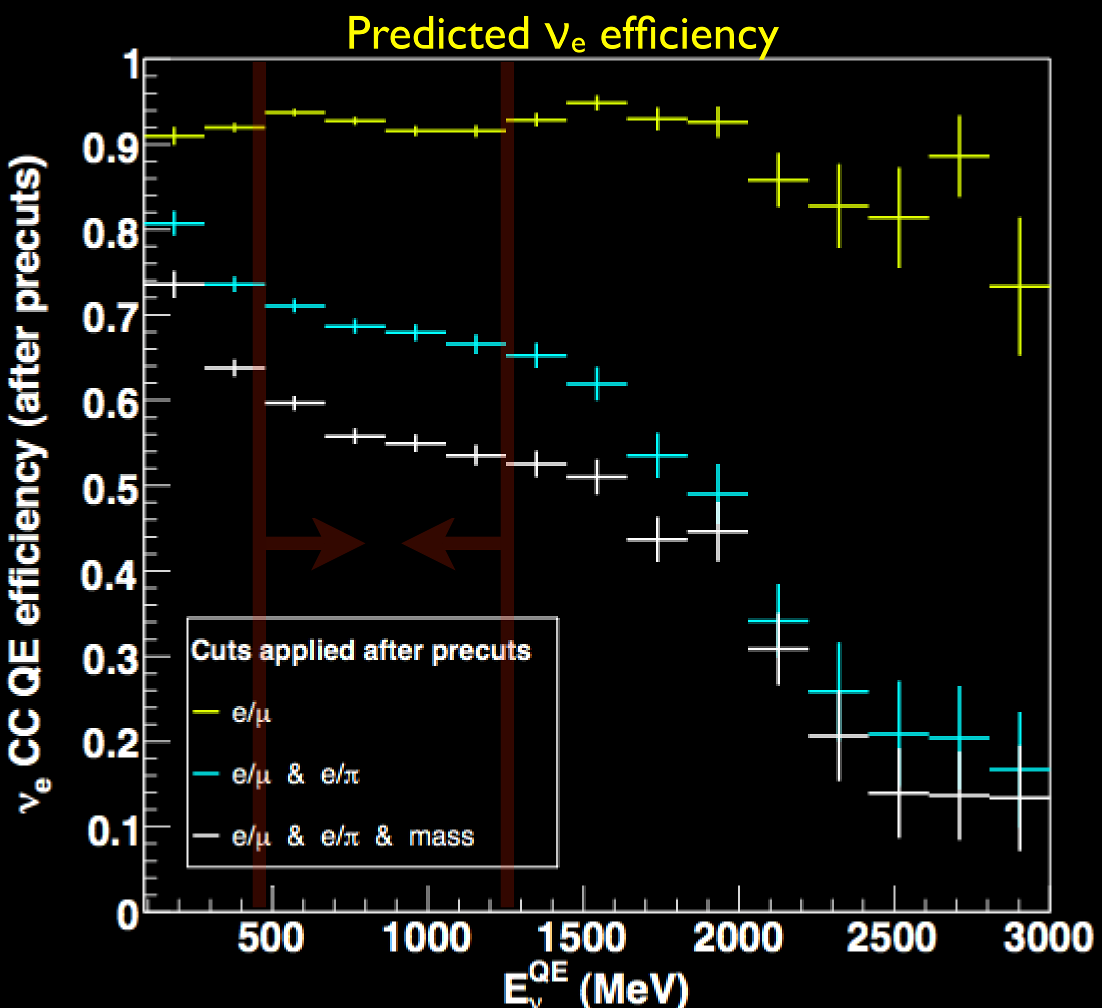


e/π^0 Likelihood

- "All but signal" (open) data and MC
- PID uses cuts on
  - likelihood ratio
  - reconstructed π^0 mass
- Opened sidebands before unblinding full data sample



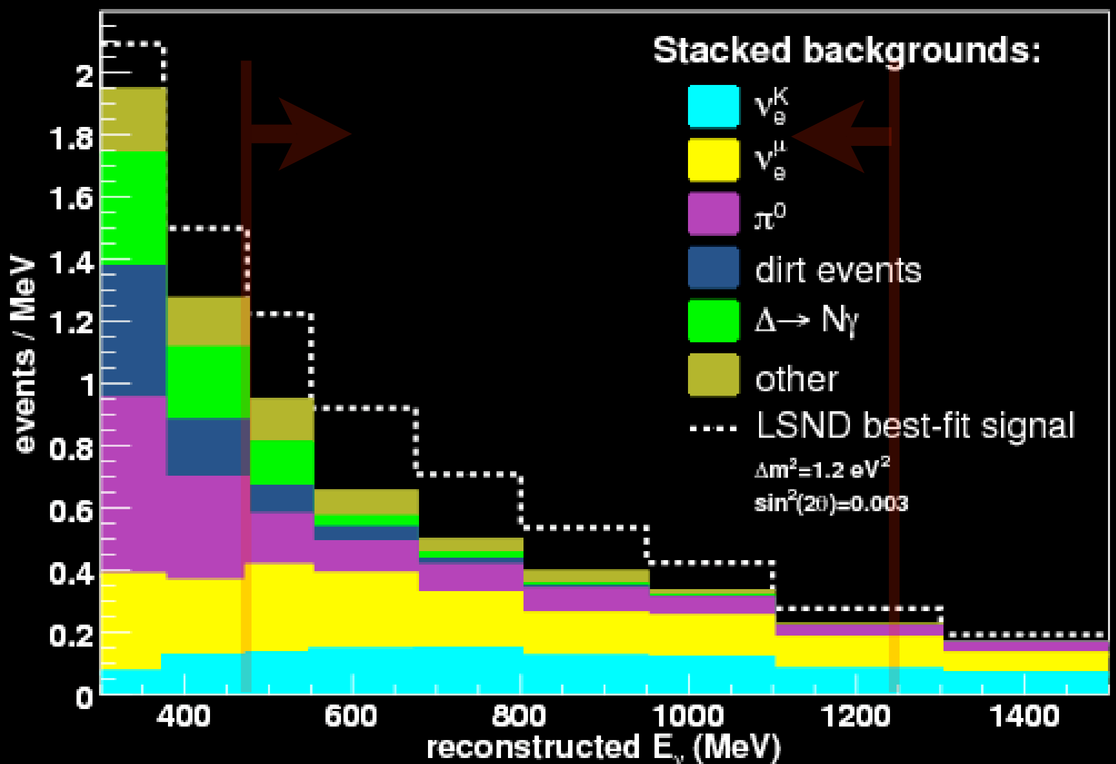
Signal and background



- "Analysis region" defined to be 475-1250 MeV
- Signal efficiency higher at low energy
- Backgrounds higher there too...

Signal and background

Predicted ν_e energy distribution



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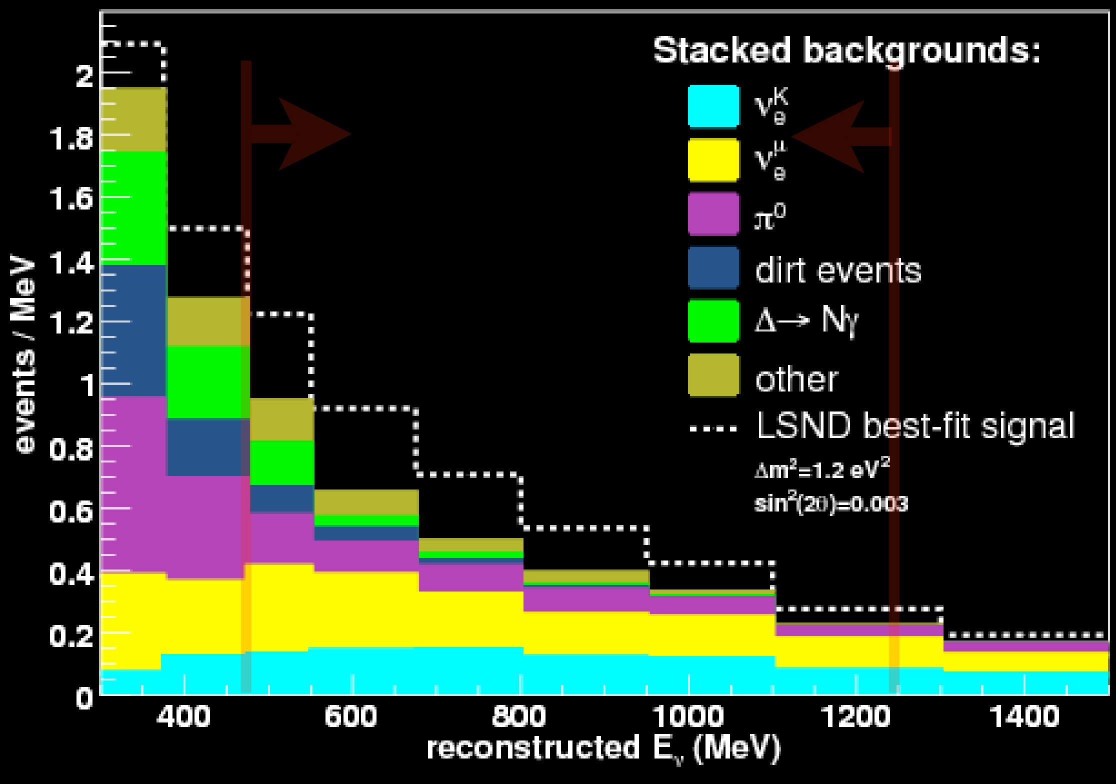
Signal and background

Predicted ν_e energy distribution



475-1250 MeV	
$\nu_e(\mu$ decay) ν_e(K decay)	132 94
Radiative Δ NCπ^0 Dirt Other	20 62 17 33
Total	*358*
Signal	*163*

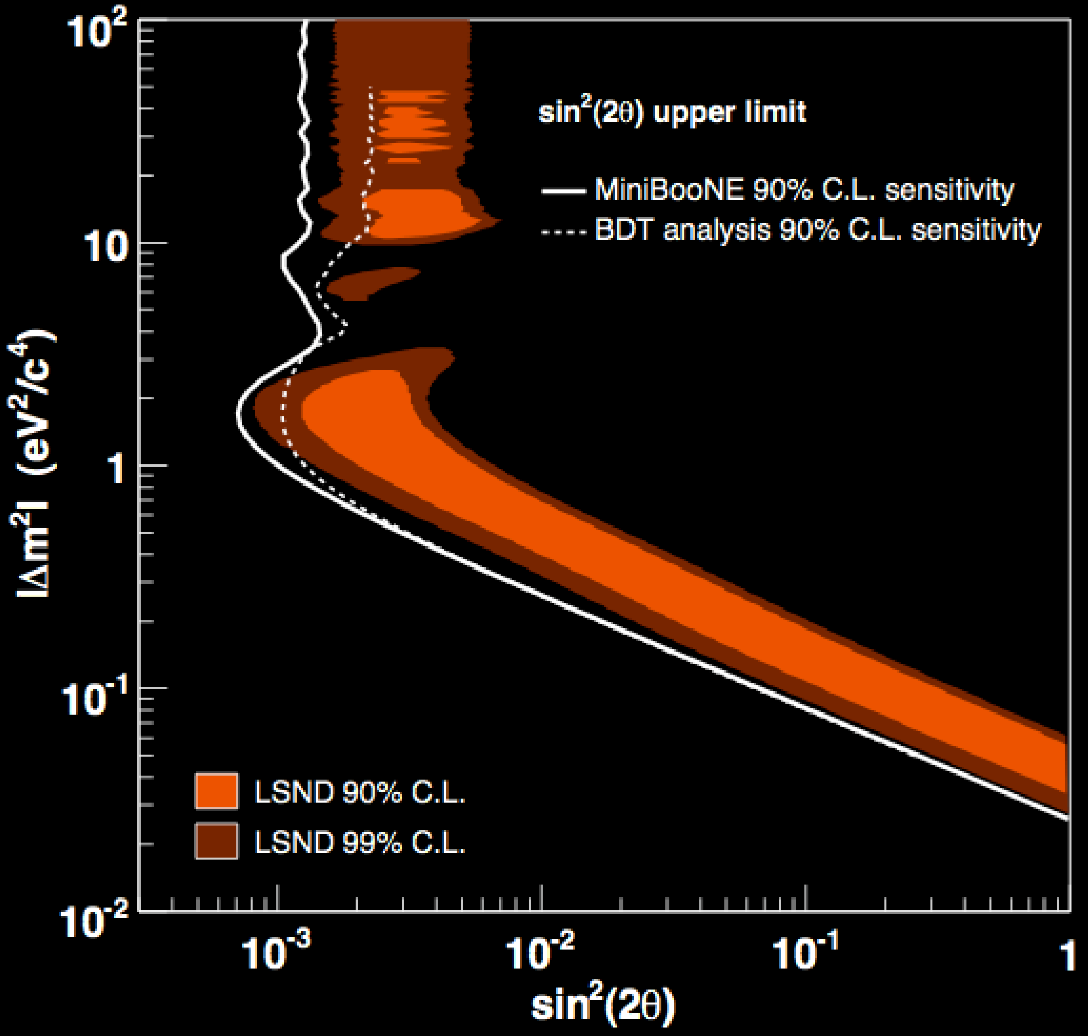
Uncertainties

	source	*uncertainty (%)*
√	Flux from π^+/μ^+ decay	6.2
√	Flux from K^+ decay	3.3
√	Flux from K^0 decay	1.5
	Target and beam models	2.8
√	ν-cross section	12.3
	NC π^0 yield	1.8
	External interactions	0.8
√	Optical model	6.1
	Electronics & DAQ model	7.5
	constrained total	9.6

Note:
"total" is **not** the quadrature sum-- errors are further reduced by constraints from ν_μ data

Sensitivity

- Sensitivity to oscillations
- "Primary" analysis chosen on the basis of this plot
  - Chosen before opening the box!



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Opening "The Box"

After applying all analysis cuts

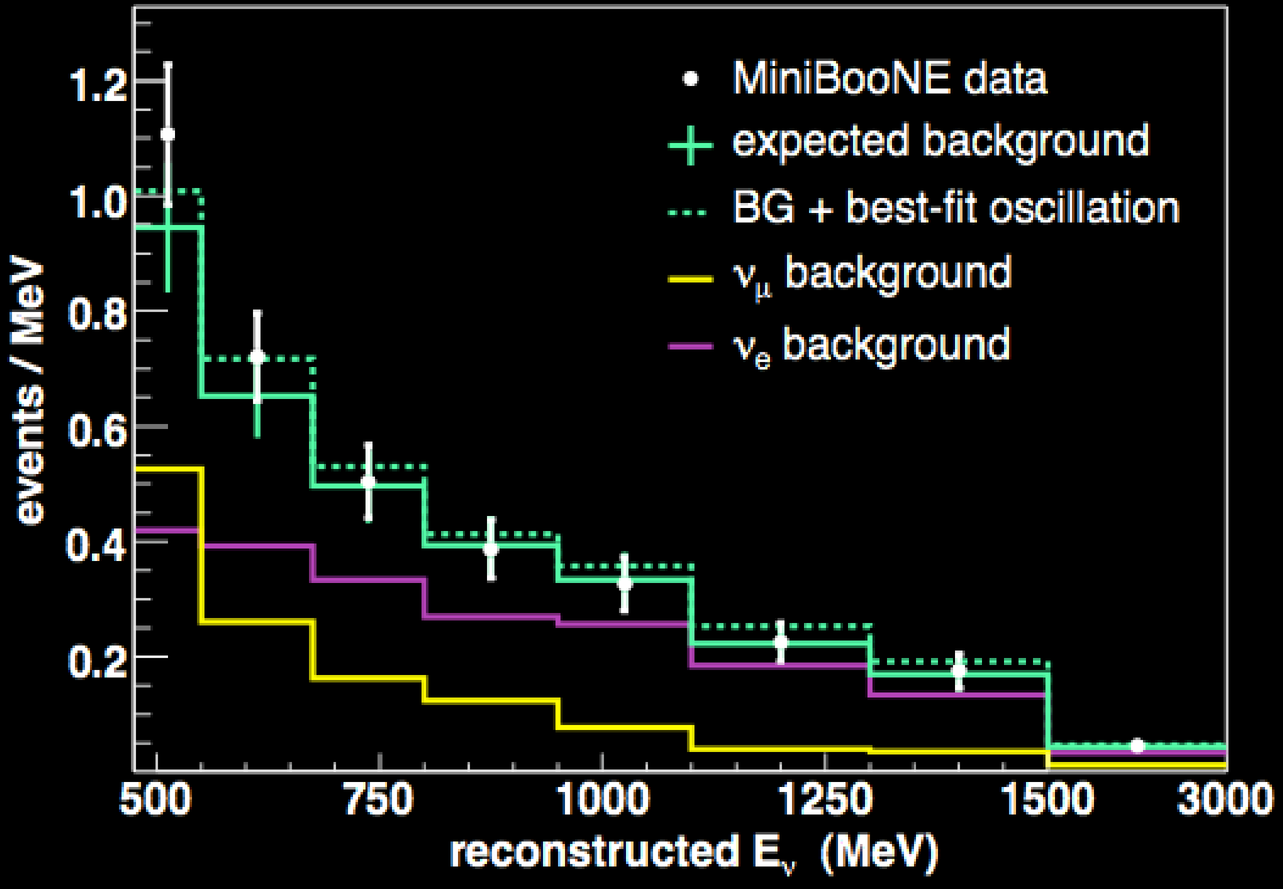
- Step 1: Fit sequestered data to oscillation hypothesis
  - ✓ Don't return fit parameters
  - ✓ Apply unreported parameters to MC, check diagnostic variables
  - ✓ Return χ^2 for diagnostic variables
- Step 2: Open plots from Step 1
  - Plots chosen to be useful but not "revealing"
- Step 3: Report only the (unsigned) χ^2 from fit
  - No fit parameters returned
- Step 4: Compare EnuQE for data and MC
  - Blindness broken
- Step 5: Present results within two weeks

Training for a blind search

MOW c. 2002
(blinded)

On March 26, 2007 we opened the box...

Opened box!

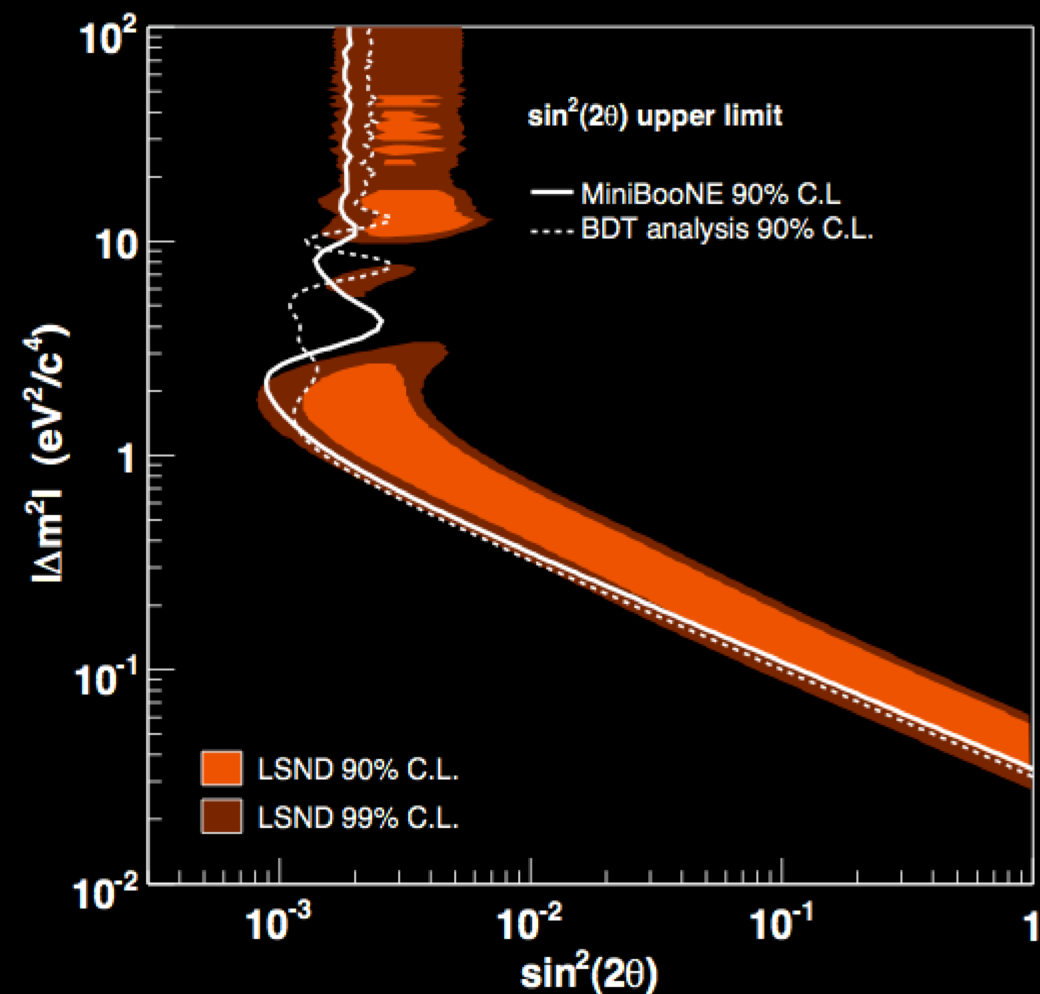


- Counting Experiment (475-1250 MeV)
- Expect 358 ± 19(stat) ± 35(sys)
- Observe 380
- Significance 0.55 σ

Exclusion Curve

- No evidence for $\nu_\mu \rightarrow \nu_e$ 2ν appearance only oscillations
- Independent second analysis finds similar result
- Incompatible with LSND at 98% CL
  - cf. KARMEN2 compatible at 64%

MiniBooNE First Result



What Does It Mean?

- With the blind analysis, we have asked the question:

Do ν_μs oscillate directly to ν_es with $\Delta m^2 \sim 1 eV^2$, ala LSND?

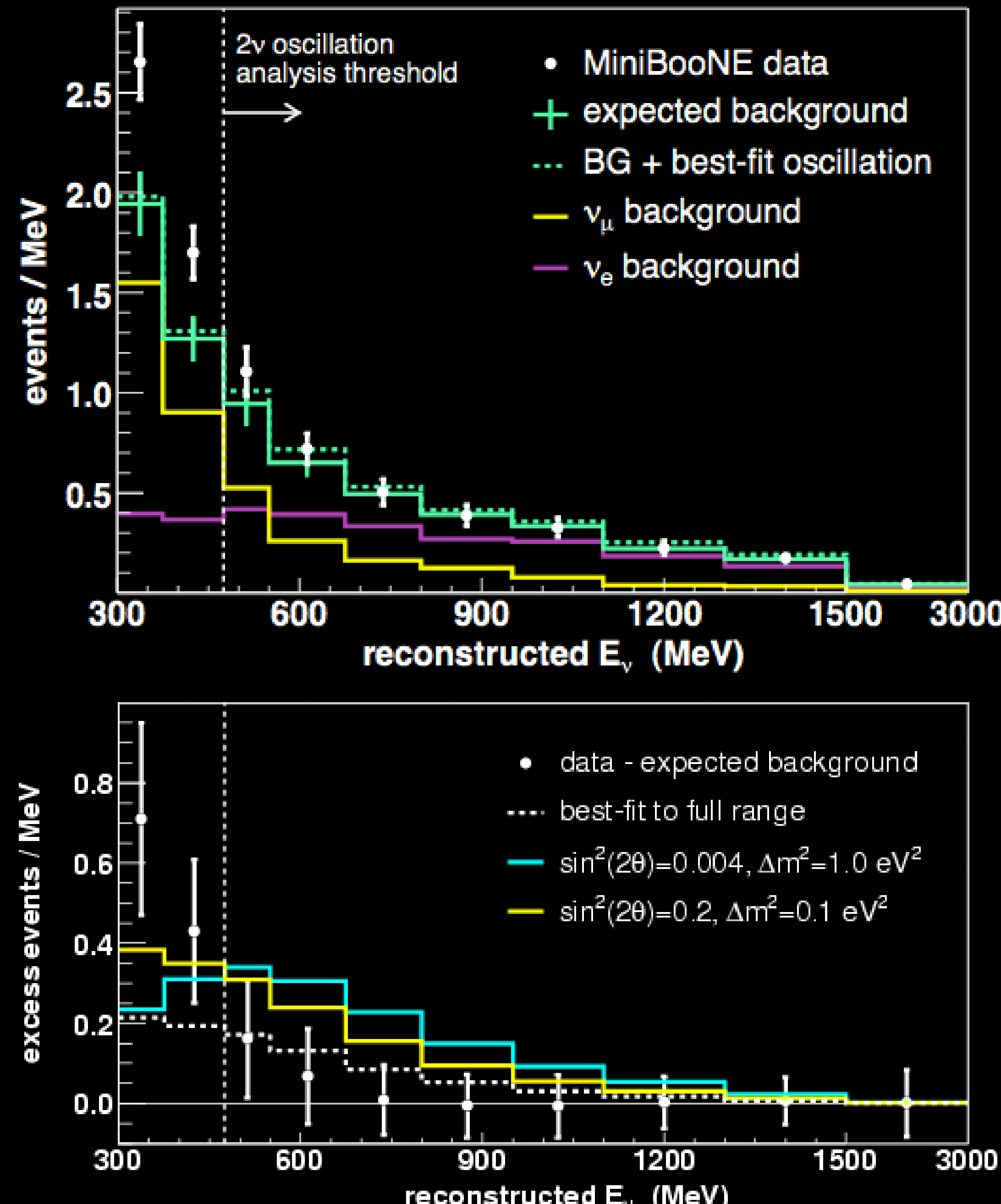
- We have a clear answer:

NO

More work yet to do...

At lower energy...

- Lowering the energy threshold reveals ν_e excess
- Excess not consistent with LSND signal
- Currently under investigation



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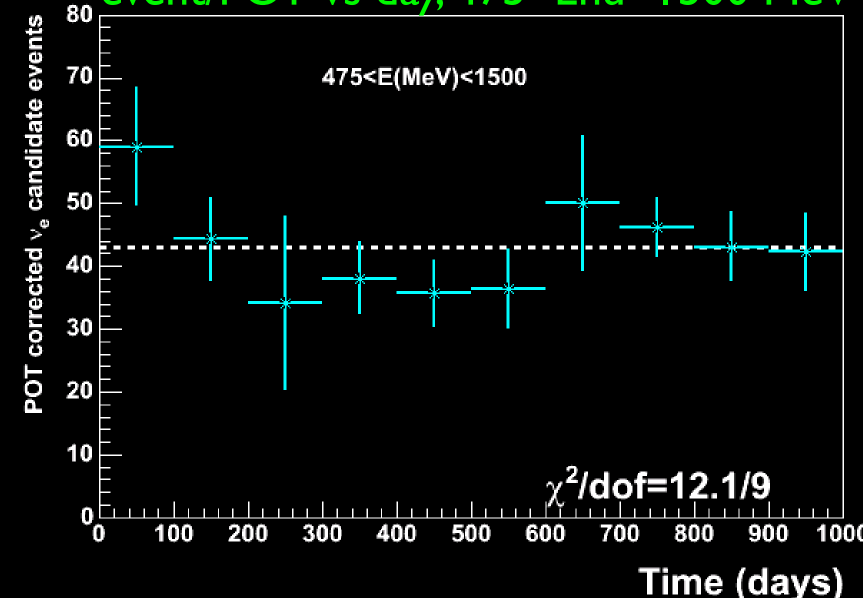
Low E checklist

- Data integrity checks
- Double check background calculations
- New backgrounds?
  - (i.e. not considered in original analysis)
  - N.B. If this is a background it may be relevant for other experiments searching for $\nu_\mu \rightarrow \nu_e$
- New physics?
- Looking at new/more data

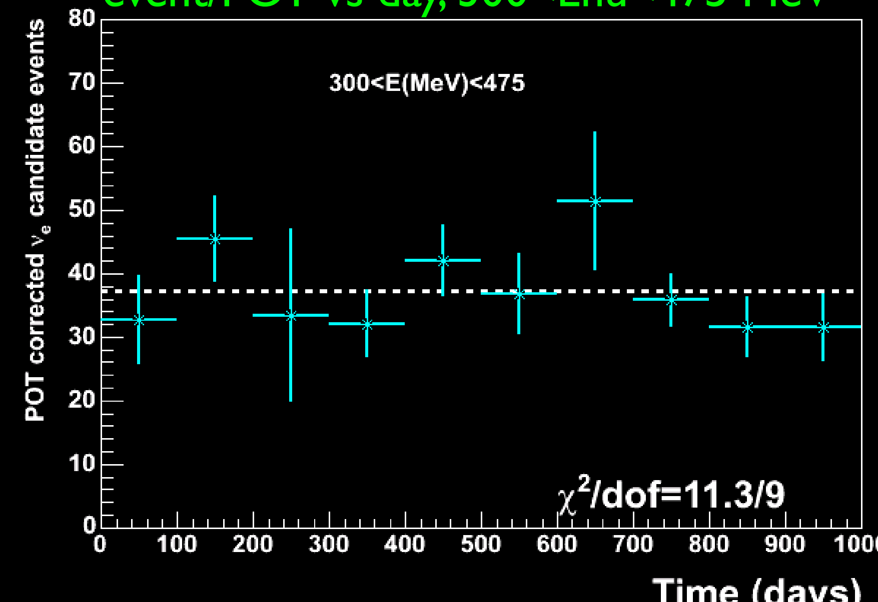
Integrity checks

- Detector anomalies: none found
  - Example: time distribution of ν_e events is flat
- Hand scanned all events: nothing pathological found

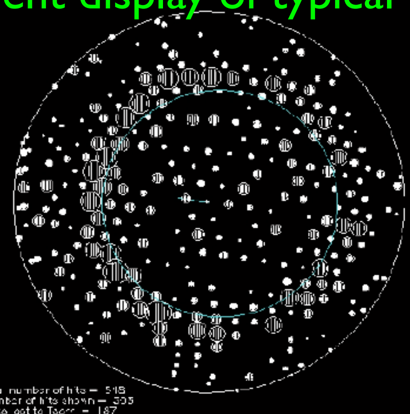
event/POT vs day, 475<Enu<1500 MeV



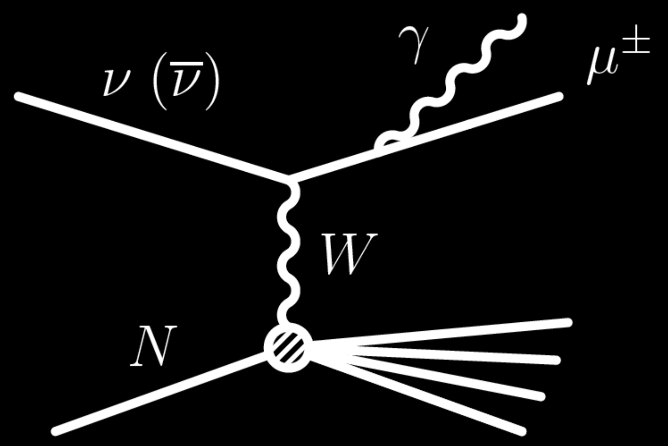
event/POT vs day, 300<Enu<475 MeV

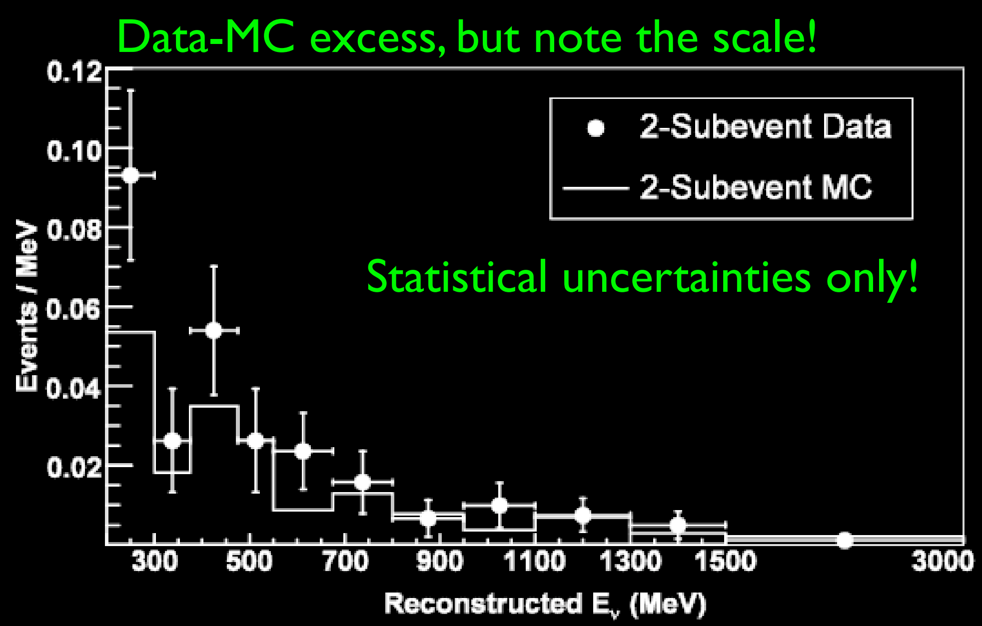


event display of typical ν_e

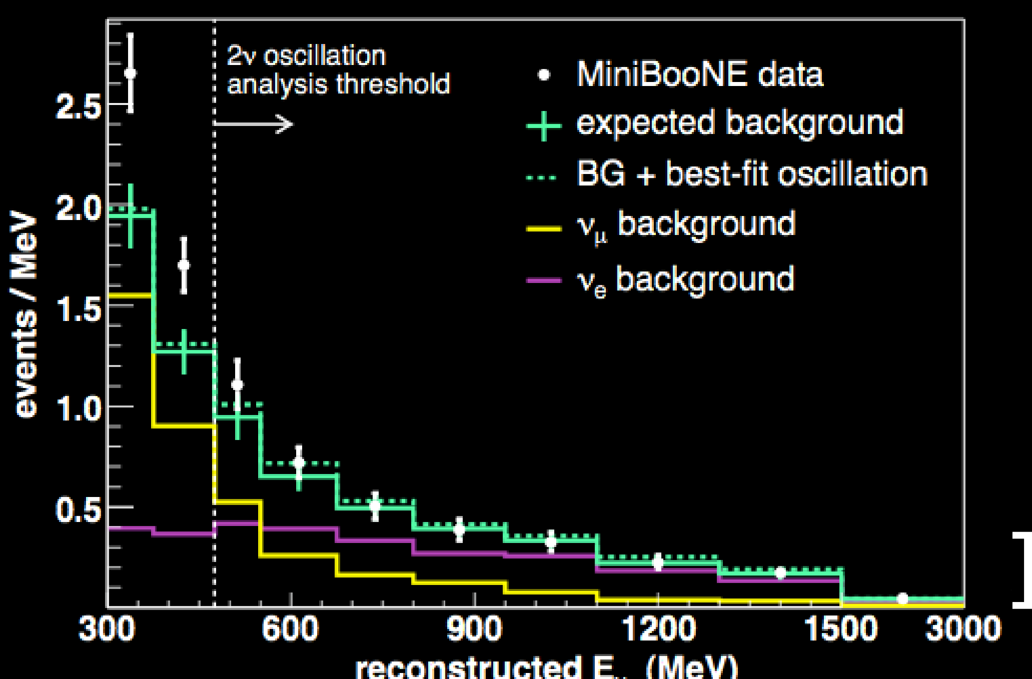


Muon Internal Brem

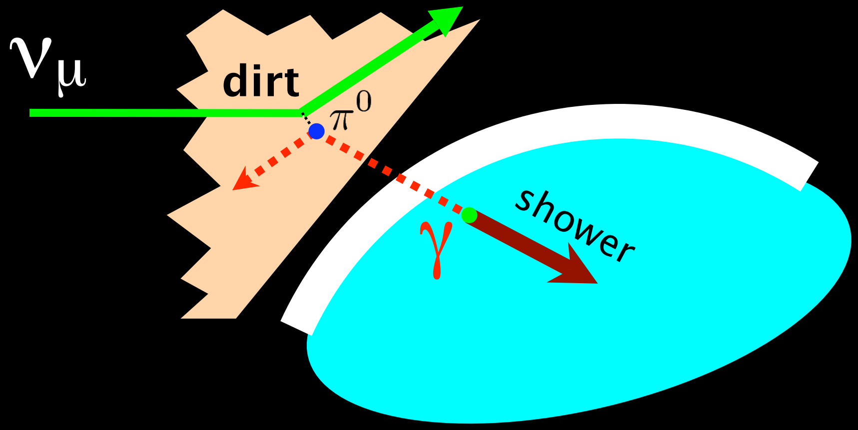




- Apply recon and PID to clean muon CCQE events
- Directly measure rate of final state muon ν_e backgrounds

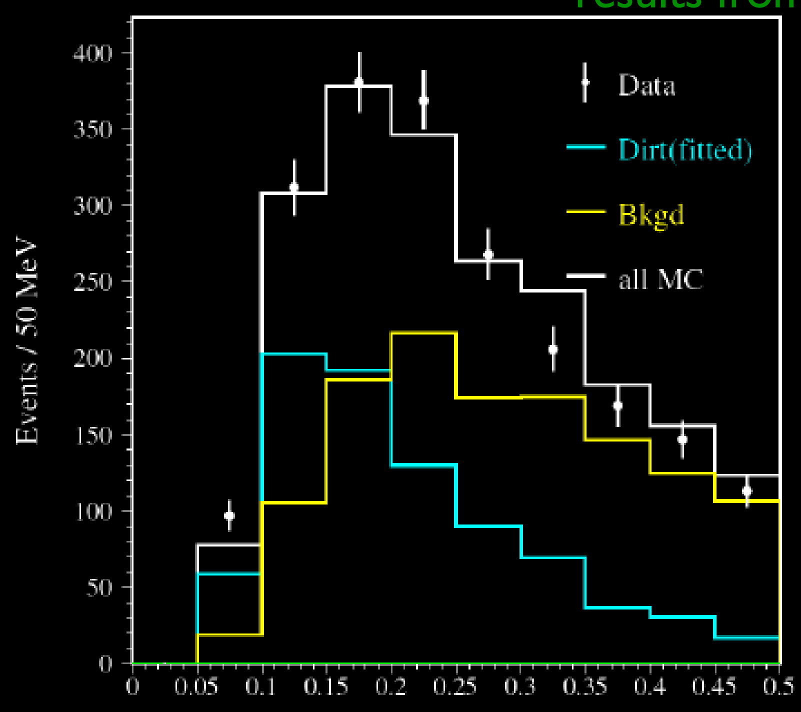


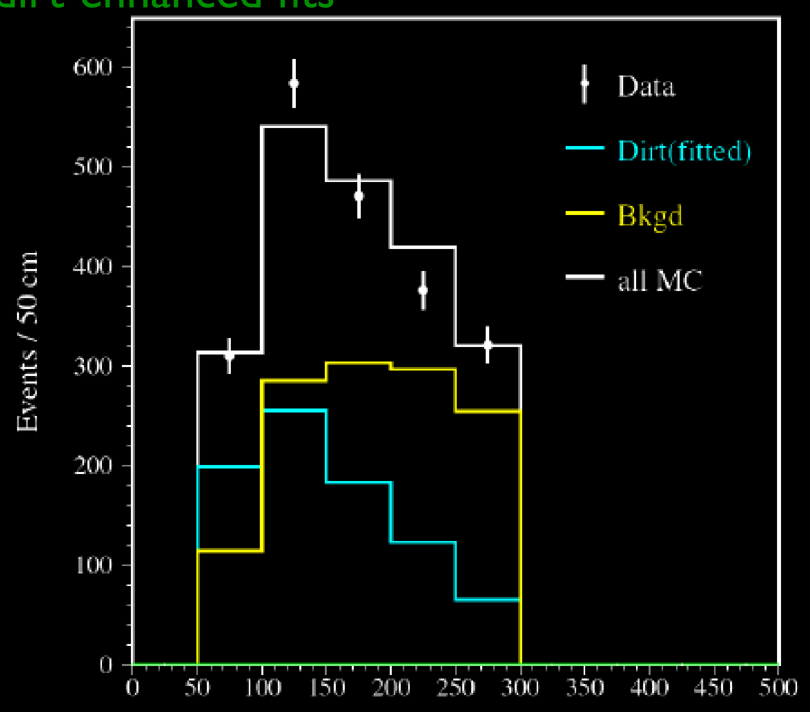
"Dirt" Backgrounds



- before box-opening, fit yielded
  - meas/pred = 1.00±0.15
- fit in different (open) sample yields
  - meas/pred = 1.08±0.12

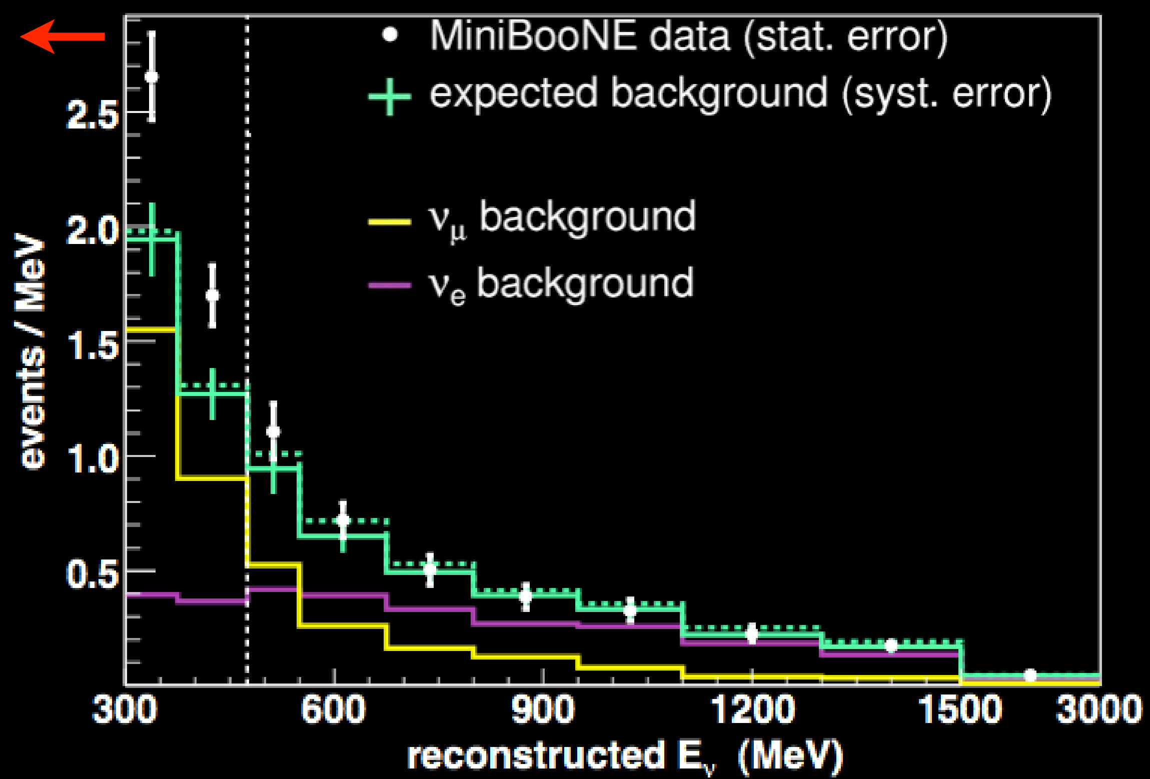
results from dirt-enhanced fits





Lower energy threshold

- More data should help
- Extended threshold to lower energy
    - required extension of systematics
- Excess persists below 300 MeV
- New bin is even more dominated by mis-ID ν_μ



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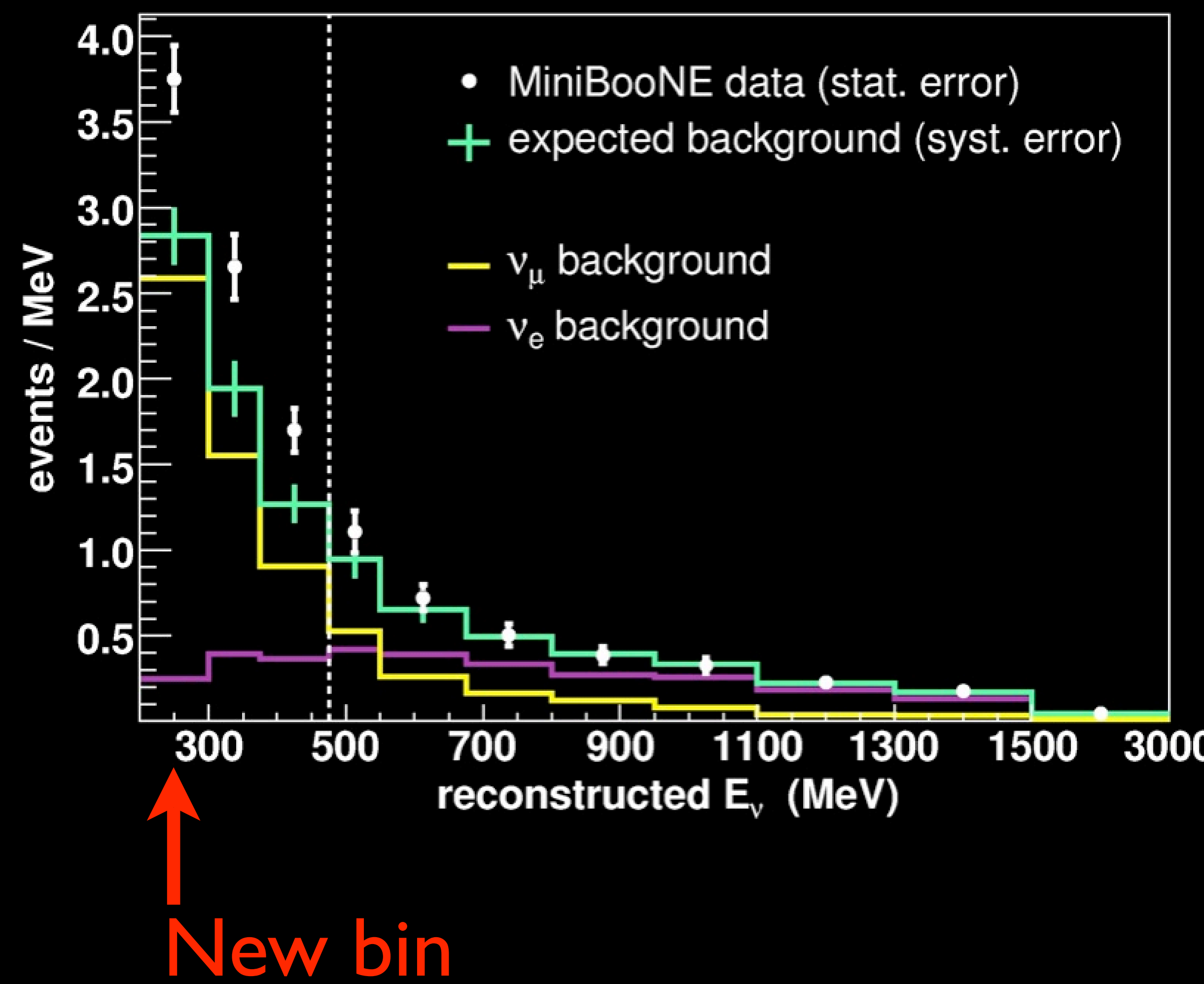
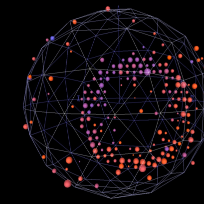


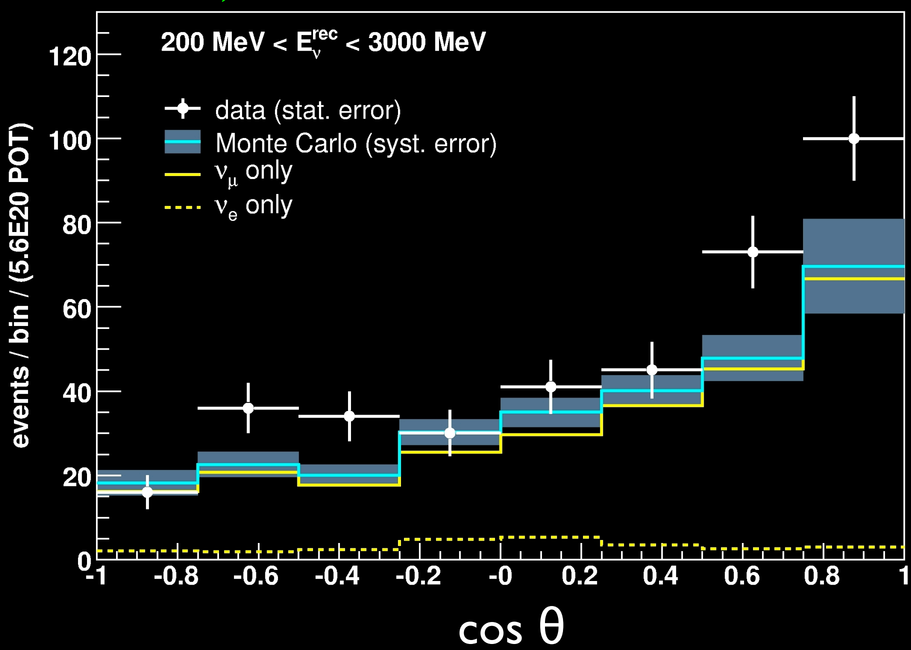
Background Breakdown

	reconstructed ν energy bin (MeV)		
	200-300	*300-475*	*475-1250*
total BG	**284±25**	**274±21**	**358±35**
ν_e *intrinsic*	26	67	229
ν_μ *induced*	258	207	129
NC π^0	*115*	*76*	*62*
NC Δ→Nγ	*20*	*51*	*20*
Dirt	*99*	*50*	*17*
other	*24*	*30*	*30*
DATA	**375±19**	**369±19**	**380±19**

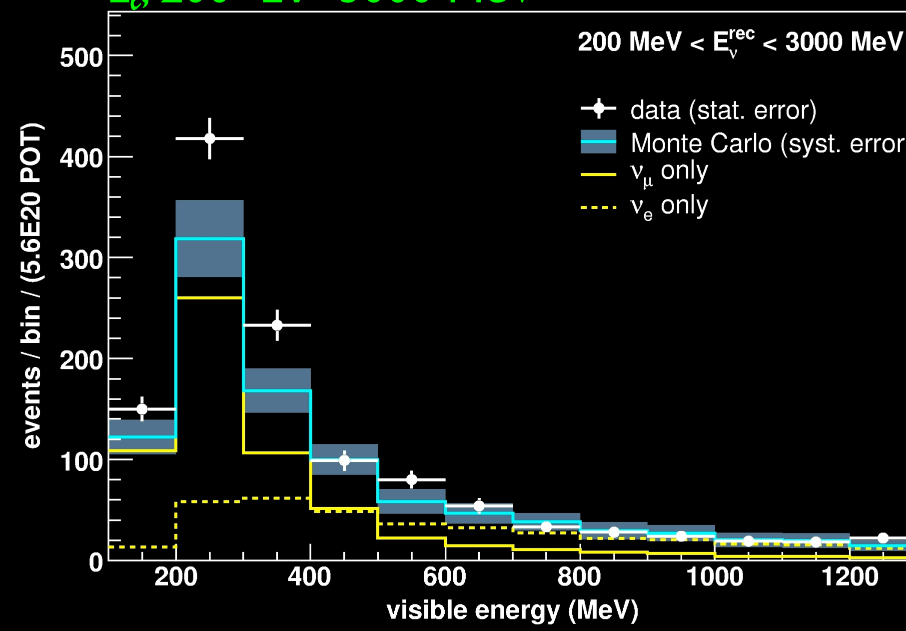
Visible Energy & Angles



cos θ , 200<Eν<3000 MeV



E_ℓ, 200<Eν<3000 MeV



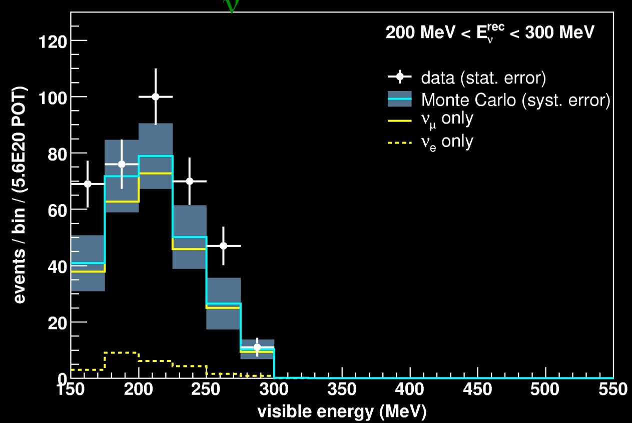
- Recall: two-body kinematics allow ν energy reconstruction from E_{lepton} and θ_{lepton}

$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}cos\theta_\ell}$$

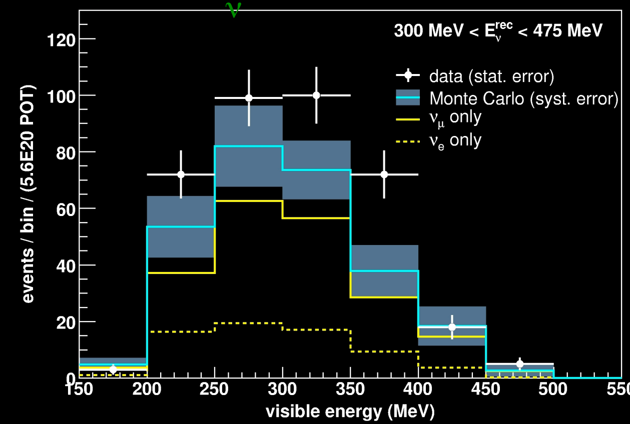
- no anomalies in these distributions

E_ℓ & θ_ℓ in E_ν bins

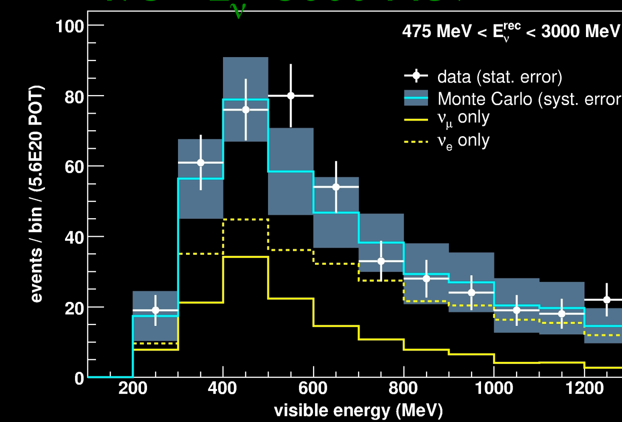
200< E_ν <300 MeV



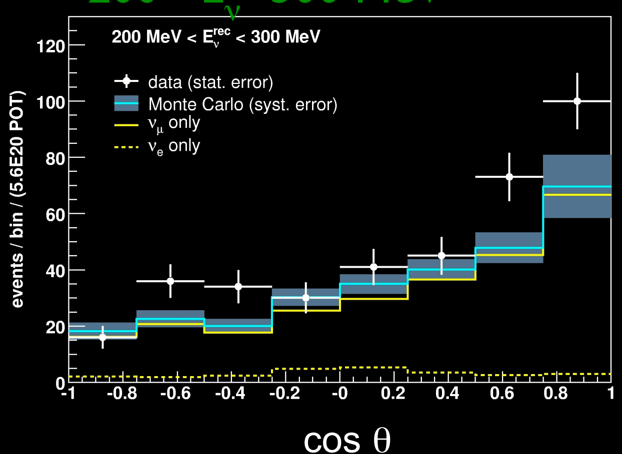
300 <E_ν <475 MeV



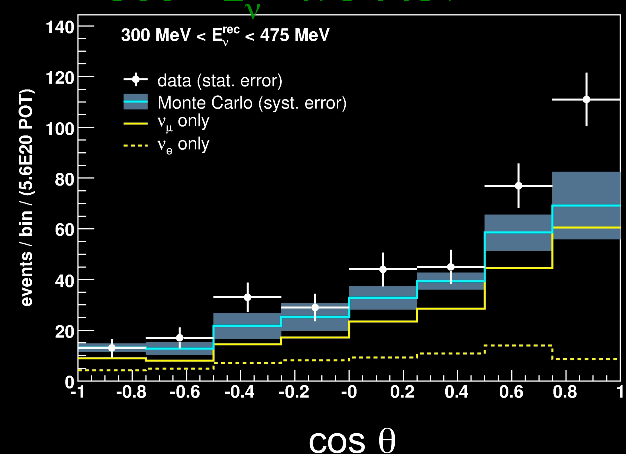
475 <E_ν <3000 MeV



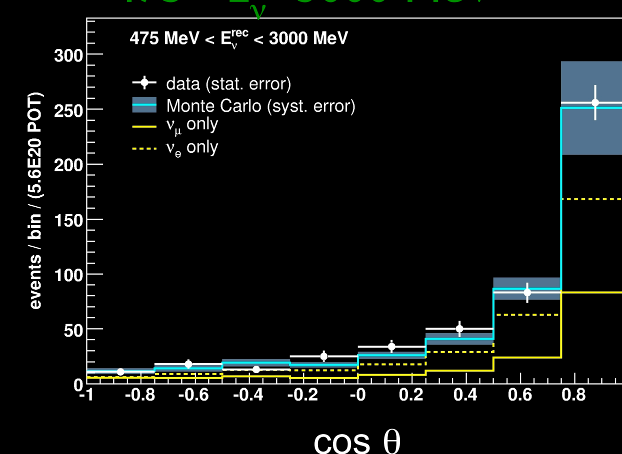
200< E_ν <300 MeV



300< E_ν <475 MeV



475< E_ν <3000 MeV



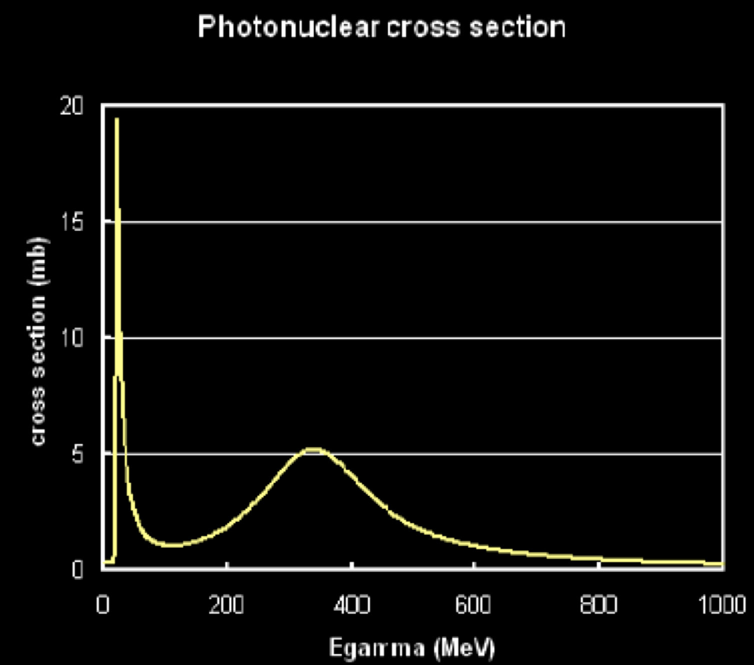
Excess distributed among E_ℓ, $\cos\theta_\ell$ bins

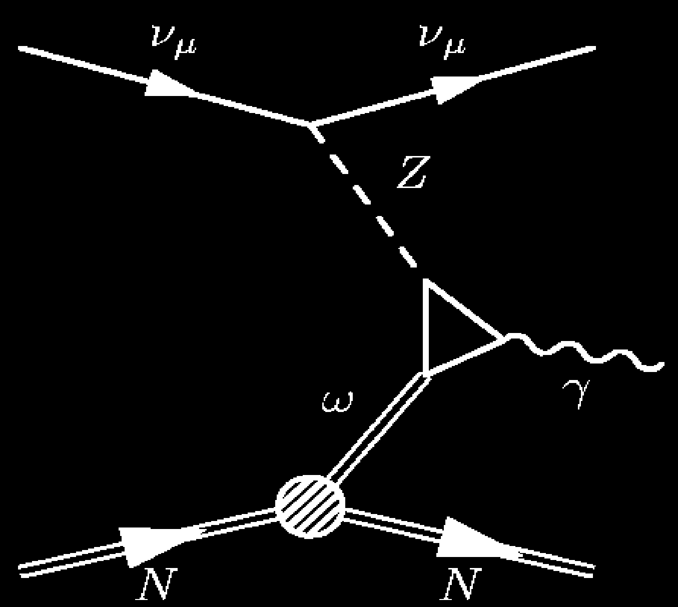
At higher energy, data are well-described by predicted background

New BG? Physics?

Difficulty distinguishing single photons from electrons

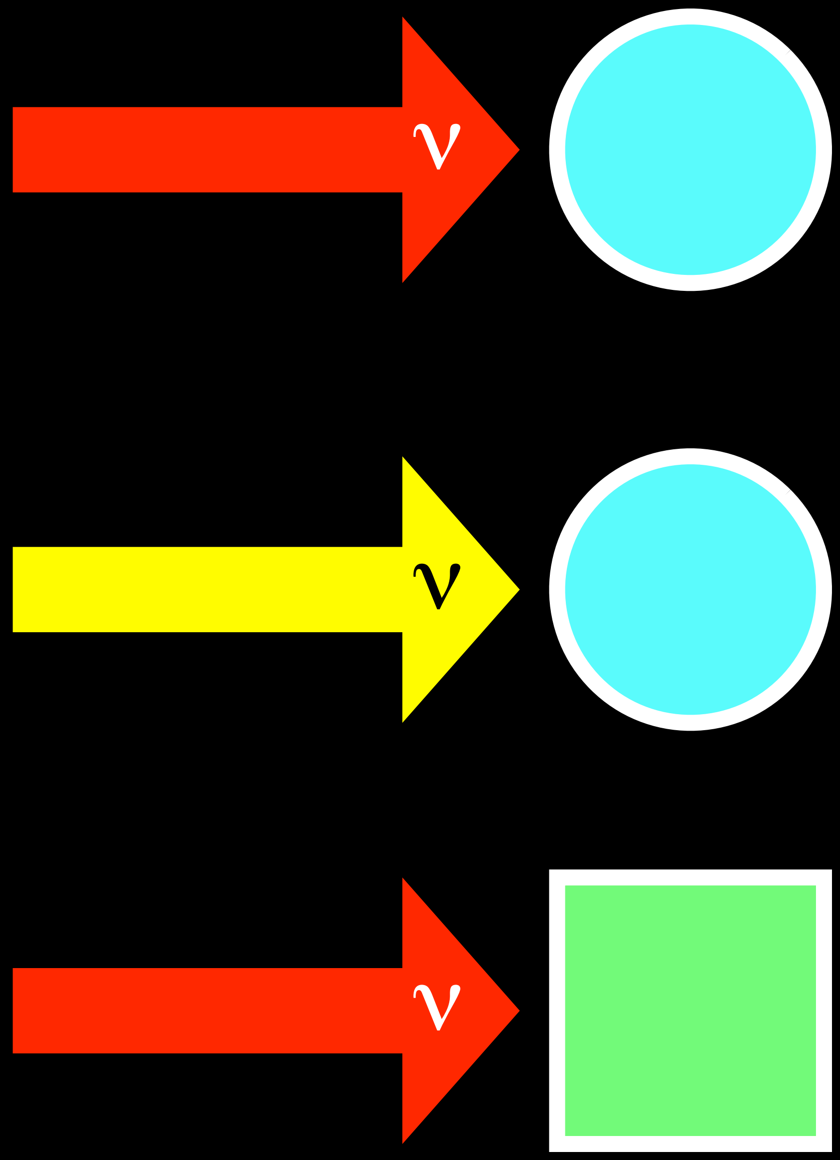
- Photo-nuclear absorption
  - Can produce low energy "ν_e" events
  - No effect on E_ν>475 MeV
- Anomaly-mediated photon production
  - arXiv:0708.1281[hep-ex]
- Both under active investigation





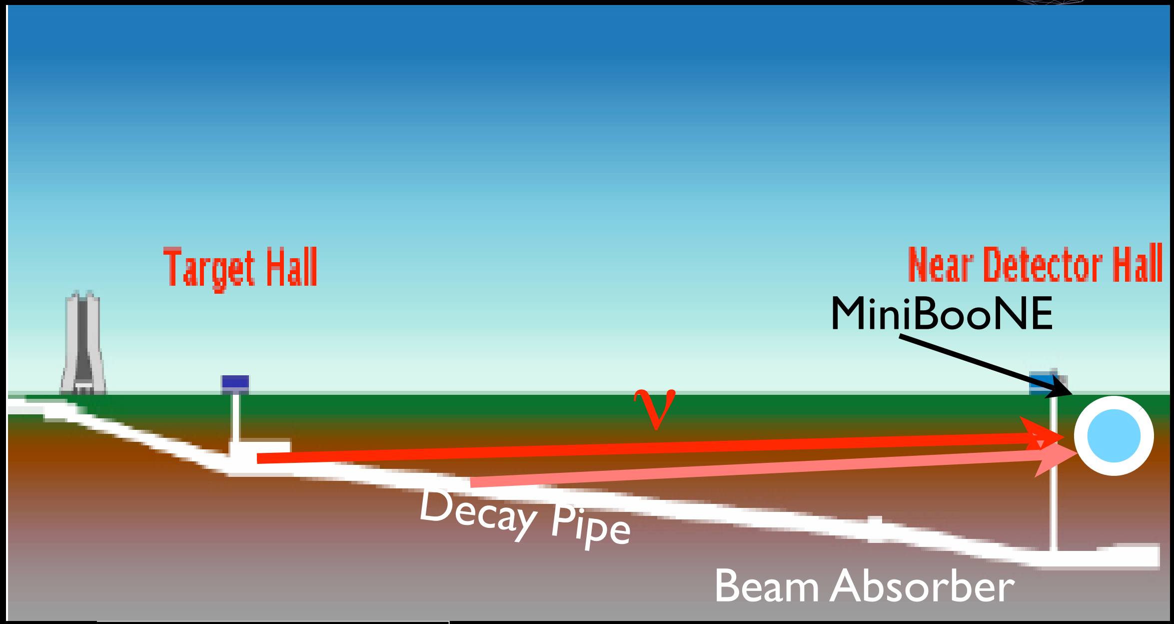
More data should help!

- Double check everything in MiniBooNE
- Same detector with different beam ⇒NuMI
- Same beam with different detector ⇒SciBooNE

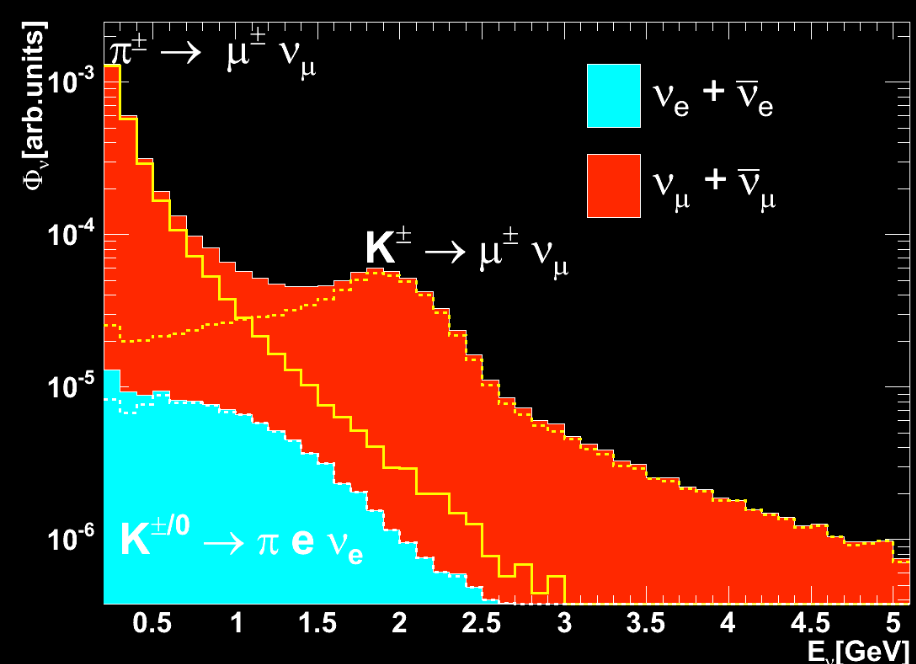


Same Det. Diff. Beam

- MiniBooNE can see neutrinos from the NuMI beam
- Off-axis beam
    - 110 mrad
- Enriched ν_e sample
    - Very different energy for ν_μ components
- Results presented Dec 14



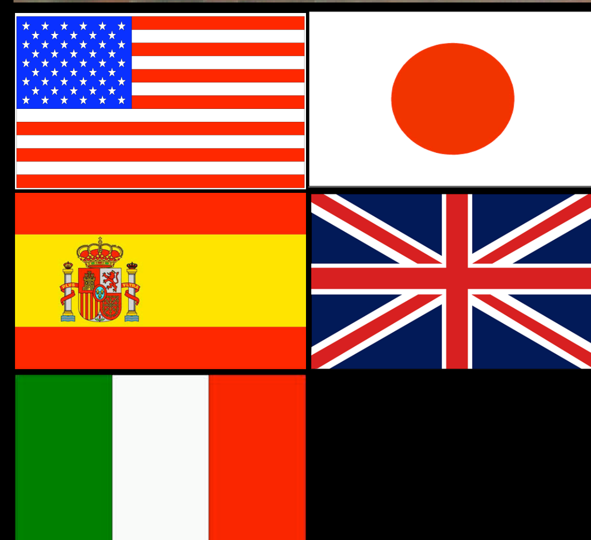
NuMI ν Flux at MiniBooNE



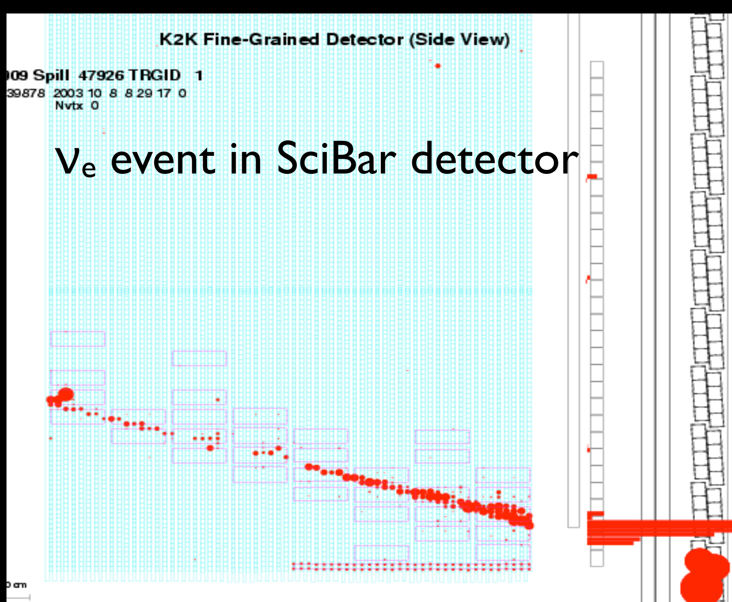
Same Beam Diff. Det.

SciBooNE

- New experiment at Fermilab
- Near Detector in BNB
- Better at distinguishing photons from electrons
    - Check MiniBooNE's background estimates

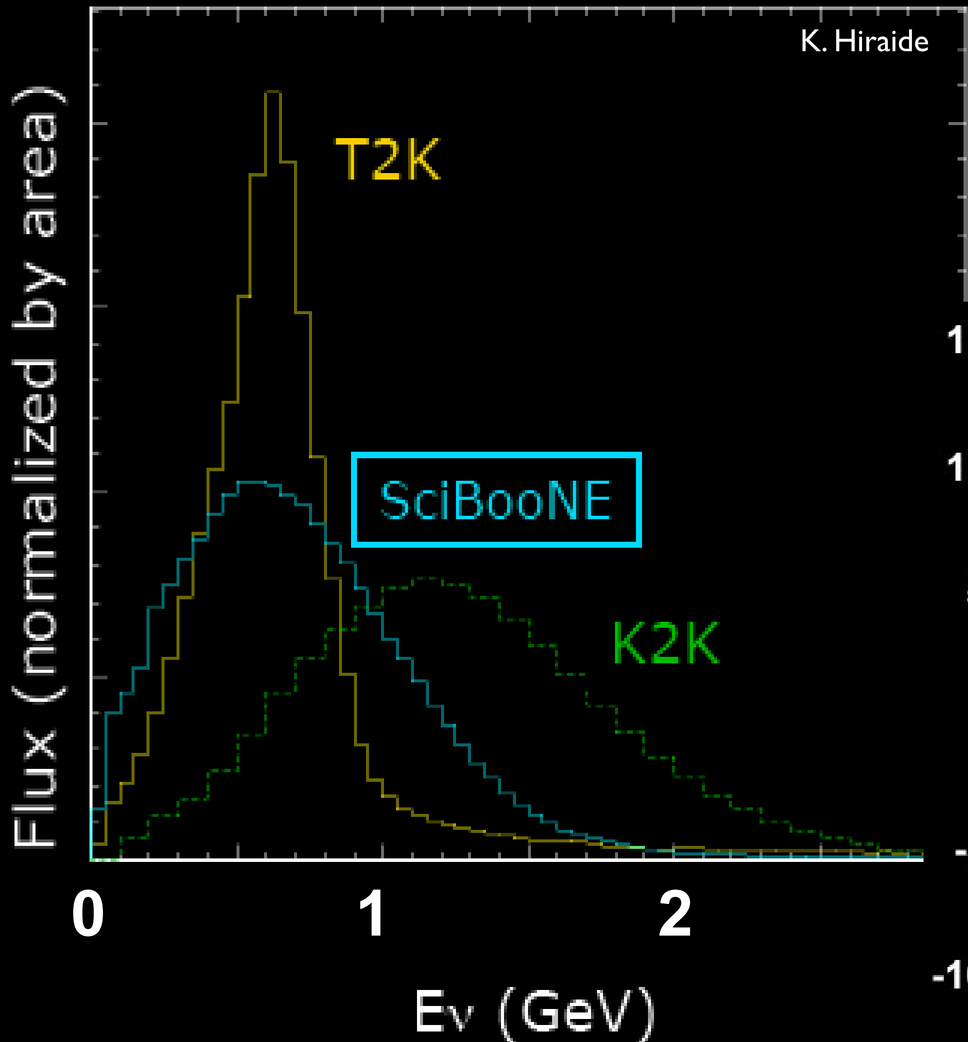


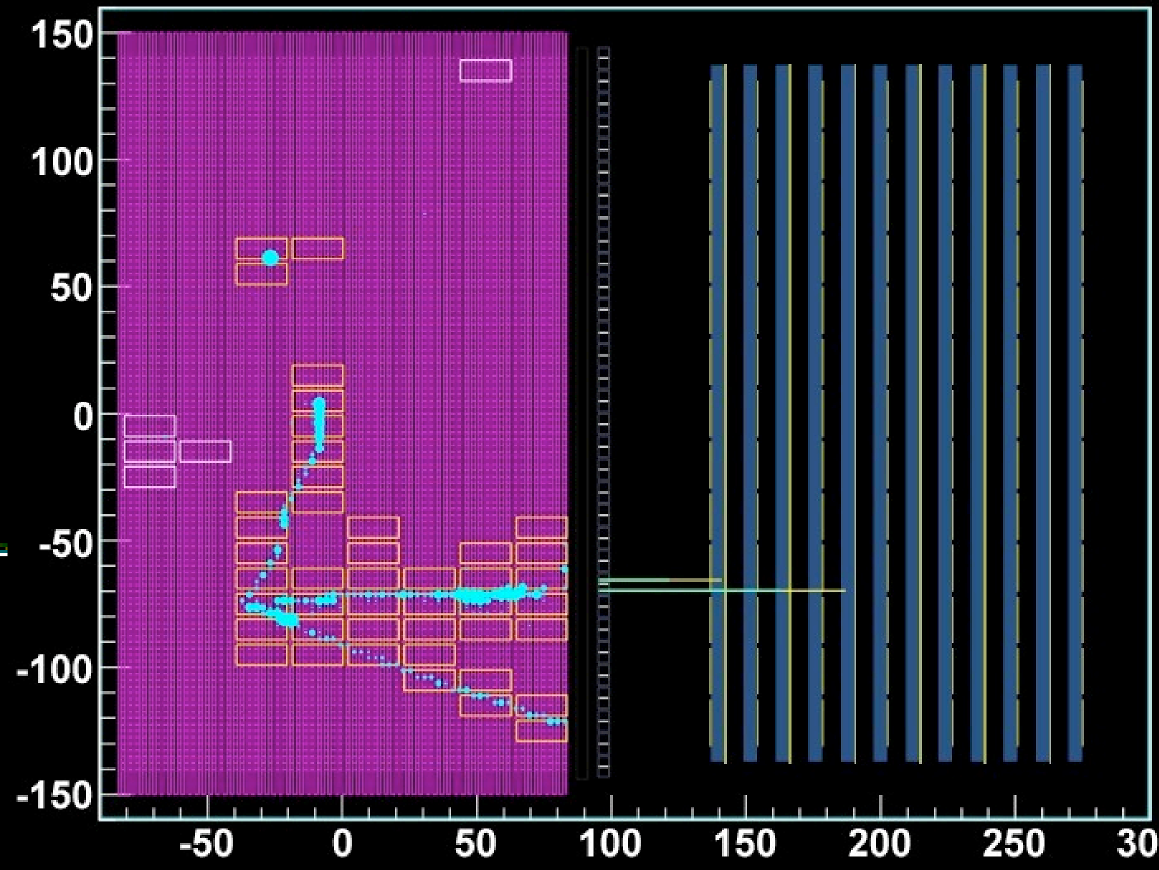
Spokespeople:
T. Nakaya, Kyoto University
M.O. Wascko, Imperial College



SciBooNE

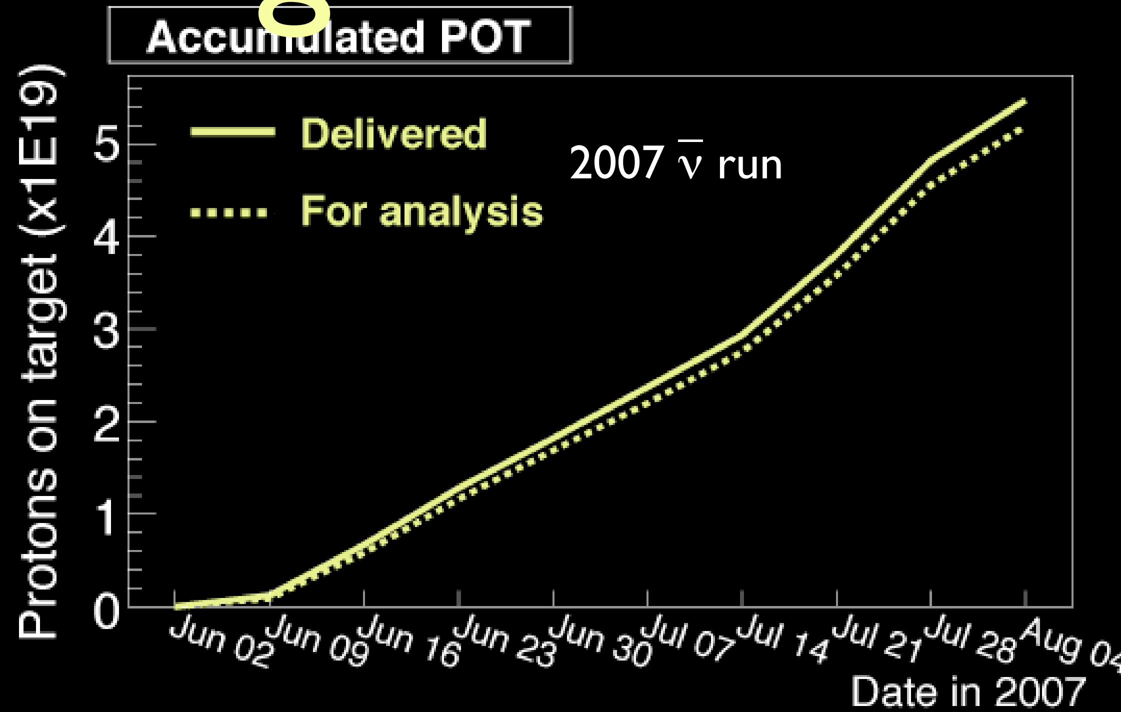
- *Three subdetectors:*
  - *SciBar, EC, MRD*
- *Data run started June 2006*
- *Now taking data (as I speak!)*

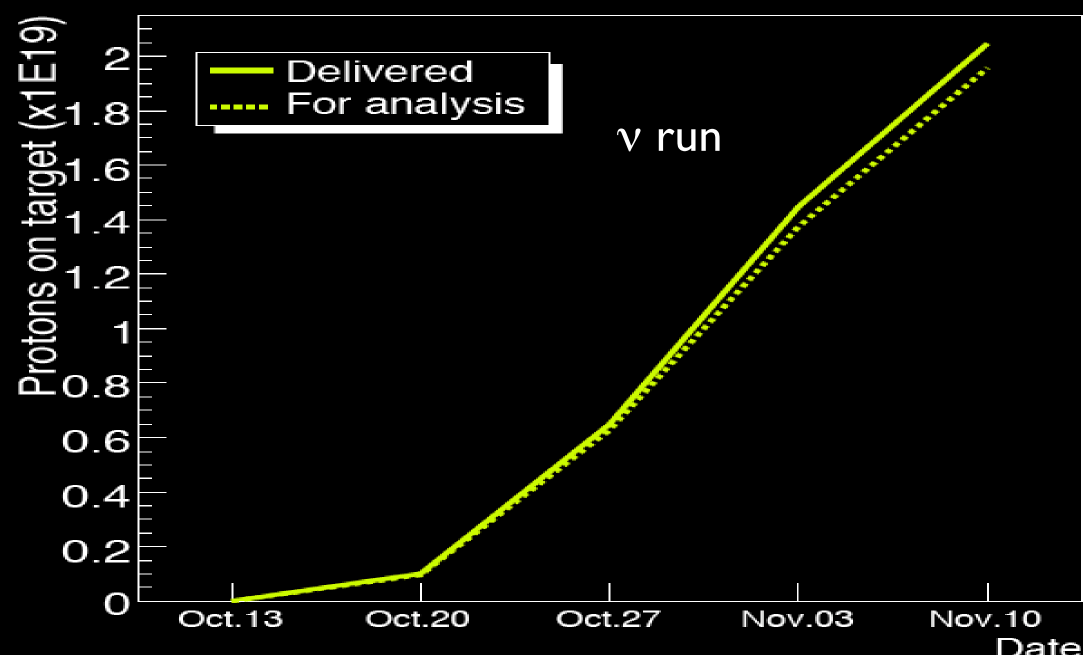




Data Progress

- Expect 2.0e20 POT total
  - 1.0e20 neutrino
  - 1.0e20 antineutrino
- Collected 0.54e20 POT antineutrinos already
- Now running in neutrino mode
  - Only 1 dead channel in 14,336+256+362





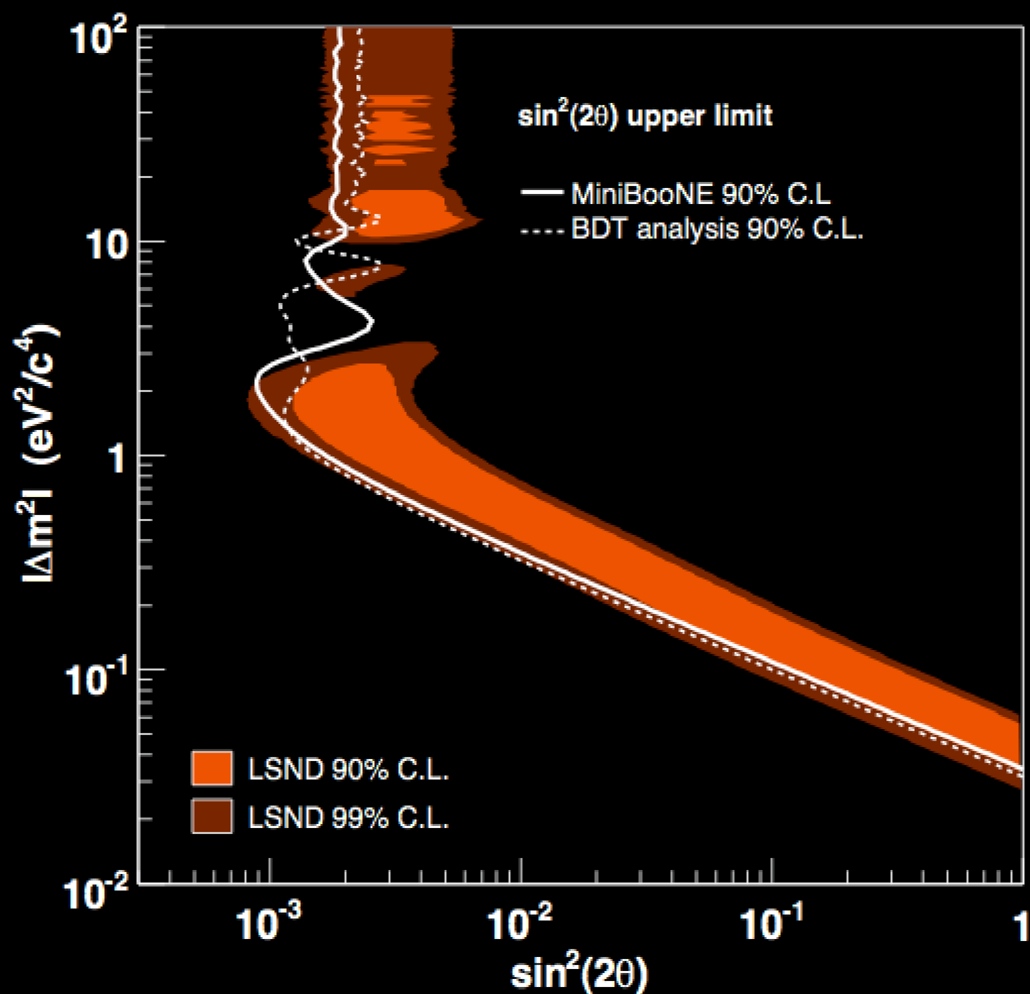
What's Next?

- MiniBooNE is publishing more papers:
  - Neutrino cross section measurements
  - Joint analysis of MiniBooNE, LSND and KARMEN data
  - More exotic oscillation analyses
    - ν_e disappearance
    - 2 or 3 sterile neutrinos with CP violation
      - MiniBooNE analysis coming soon
- Results of NuMI-MB analysis very soon
  - Fermilab "Wine & Cheese" Seminar Dec 14
- MiniBooNE is pursuing $\bar{\nu}_e$ appearance search now

Summary

- MiniBooNE observes no evidence for $\nu_\mu \rightarrow \nu_e$ 2ν oscillations
- Incompatible with LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation signal at 98% CL
- Low energy excess under investigation
  - More data coming soon

MiniBooNE First Result



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arXiv:0704.1500 [hep-ex]